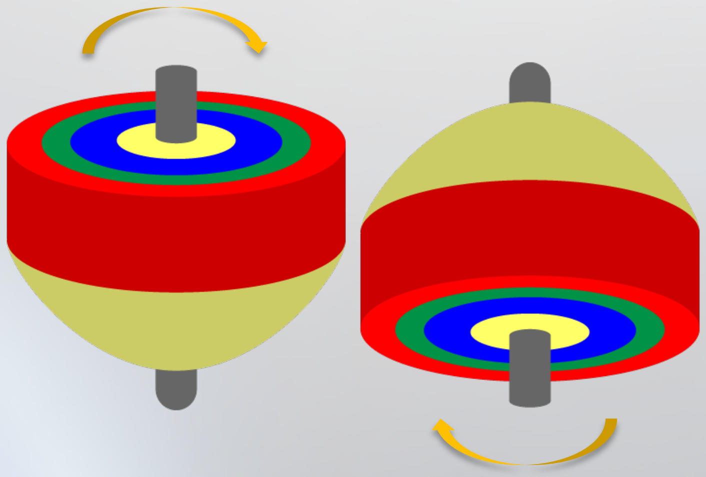
Observation of Toponium



李海峰

山东大学（青岛）

强子物理在线论坛，主持人：张鸿飞 教授

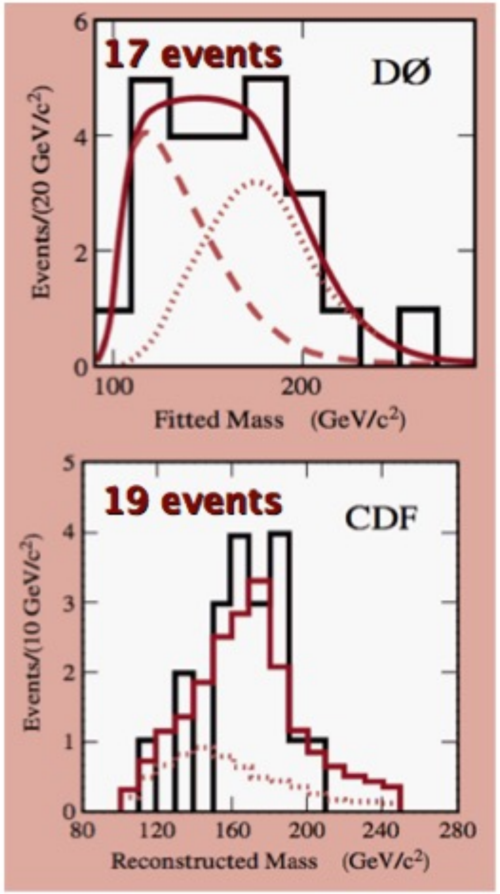
2025年12月26日

https://indico.itp.ac.cn/event/392/

Top Quark Discovery: 30周年

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

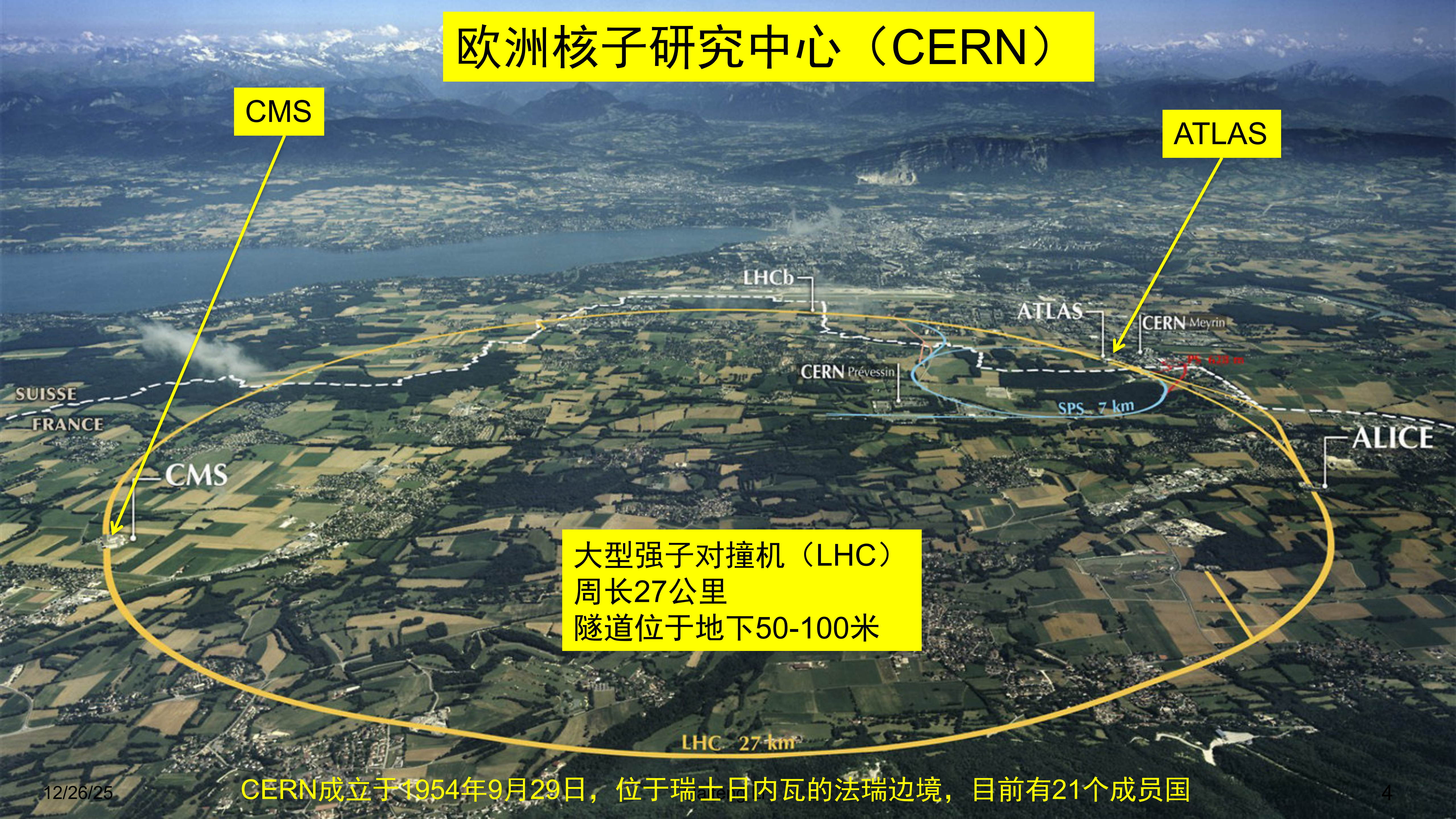
March 2nd, 1995:

First announcement of Top Discovery in public seminar at Fermilab

March 2nd, 1995:
First announcement of Top Discovery
in public seminar at Fermilab

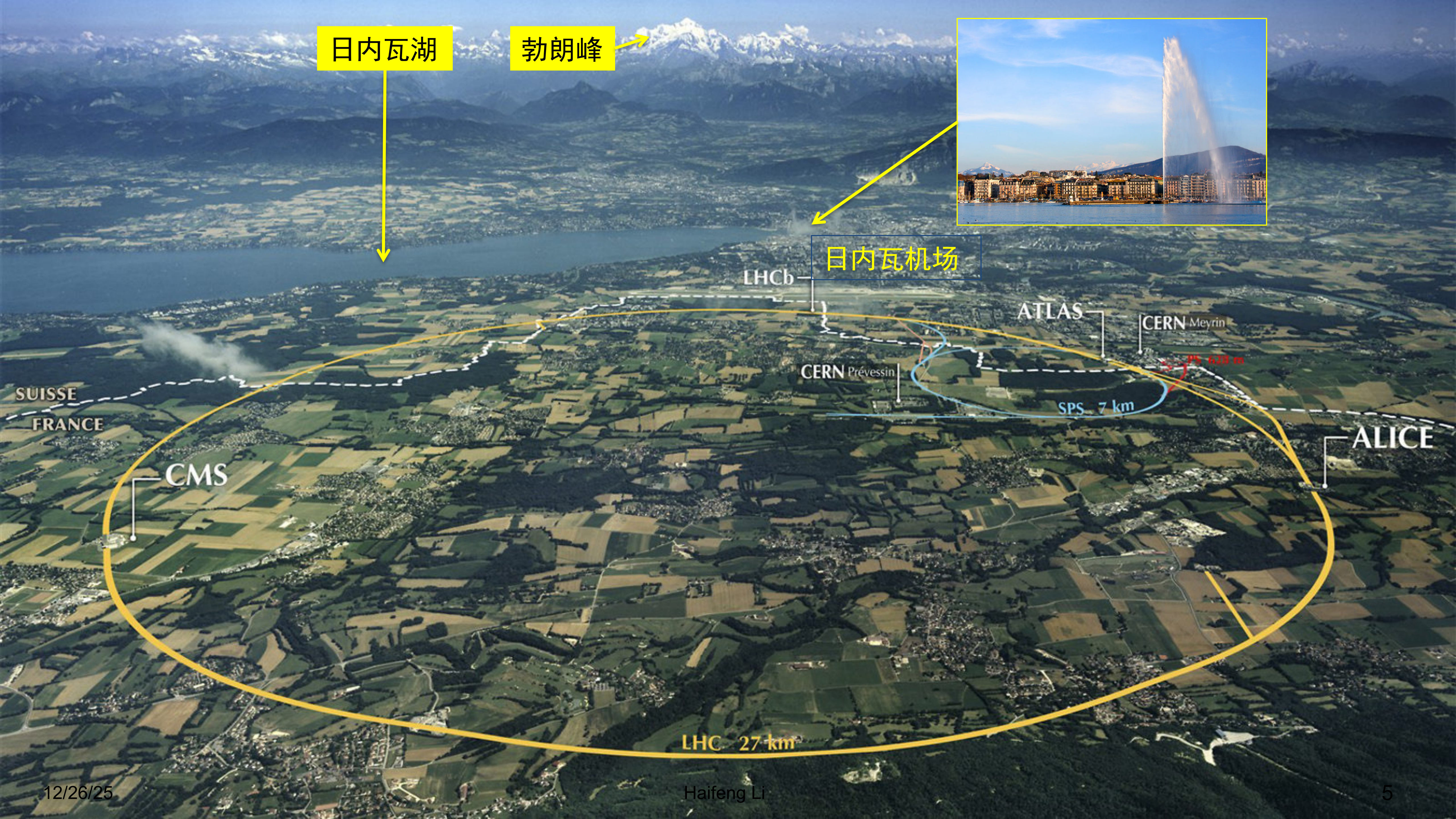
July 4th, 2012: Higgs discovery

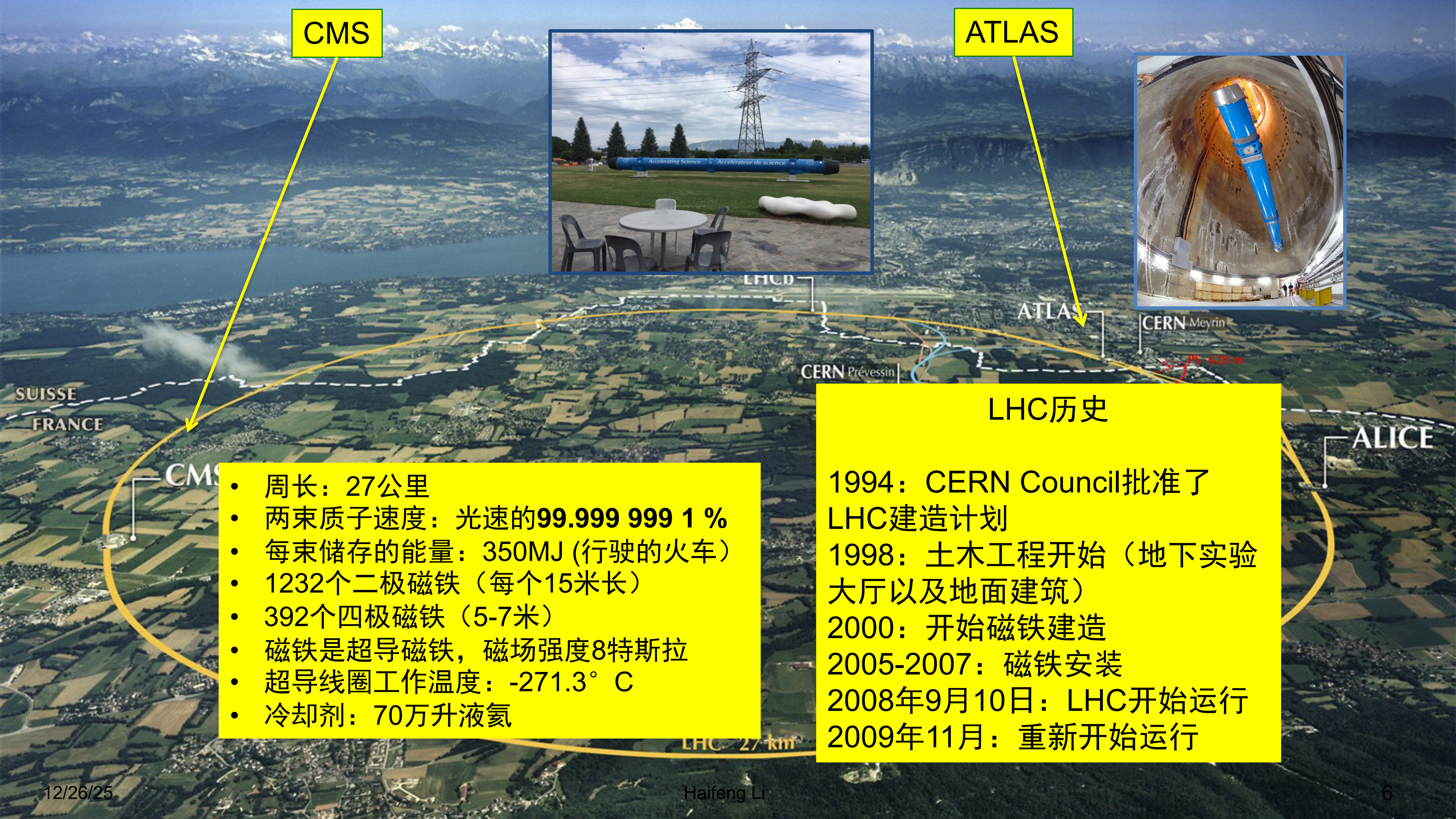
欧洲核子研究中心（CERN）



大型强子对撞机（LHC）
周长27公里
隧道位于地下50-100米

CERN成立于1954年9月29日，位于瑞士日内瓦的法瑞边境，目前有21个成员国


日内瓦湖
勃朗峰
日内瓦机场
LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km



- 周长：27公里
- 两束质子速度：光速的**99.999 999 1 %**
- 每束储存的能量：350MJ (行驶的火车）
- 1232个二极磁铁（每个15米长）
- 392个四极磁铁（5-7米）
- 磁铁是超导磁铁，磁场强度8特斯拉
- 超导线圈工作温度：-271.3° C
- 冷却剂：70万升液氦

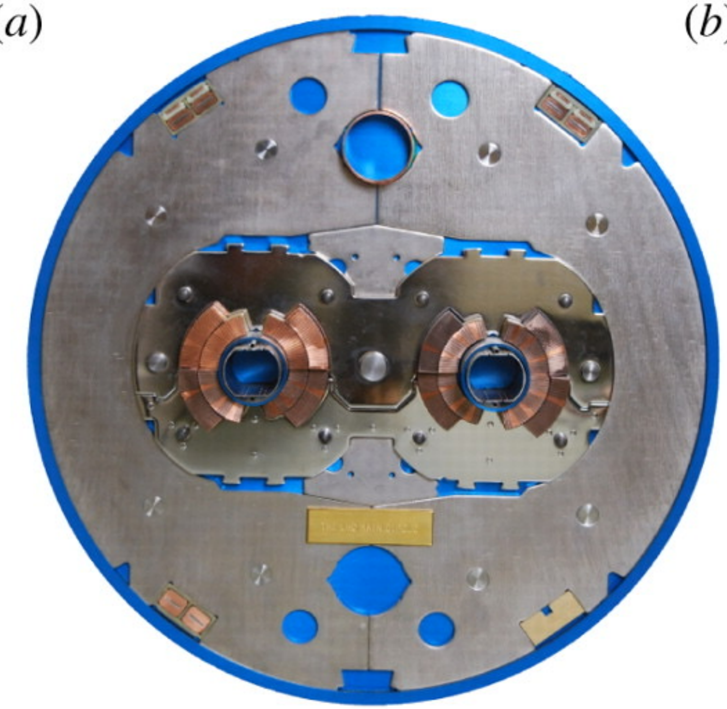
LHC历史

1994：CERN Council批准了LHC建造计划
1998：土木工程开始（地下实验大厅以及地面建筑）
2000：开始磁铁建造
2005-2007：磁铁安装
2008年9月10日：LHC开始运行
2009年11月：重新开始运行

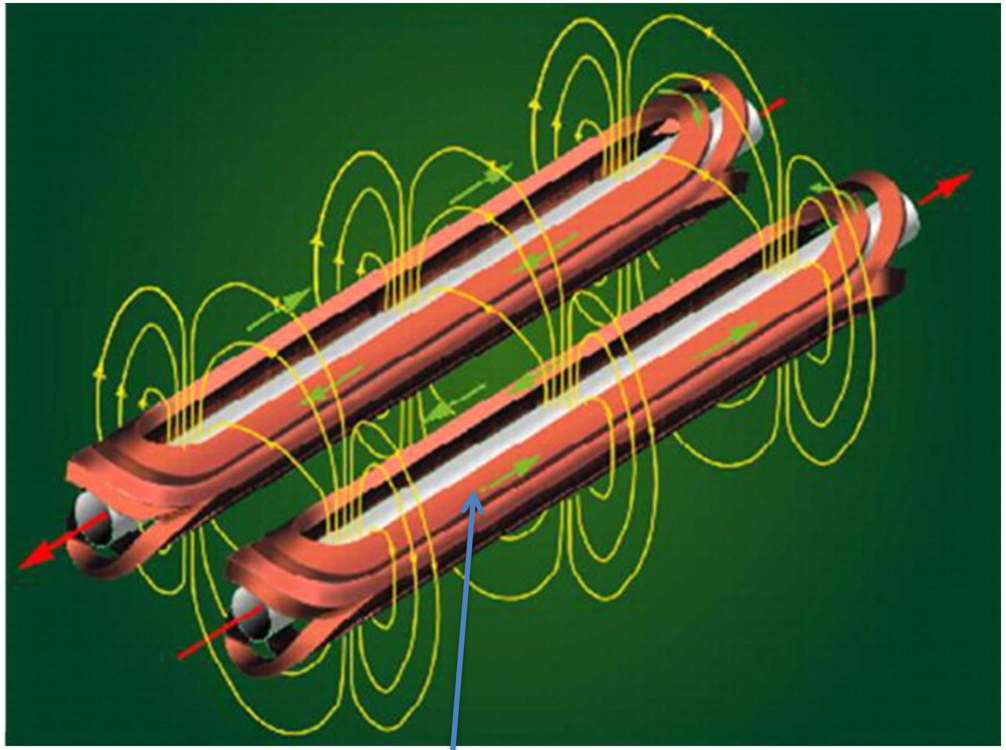
二极磁铁

两束带电质子朝相反方向运行。需要方向相反的磁场

(a)



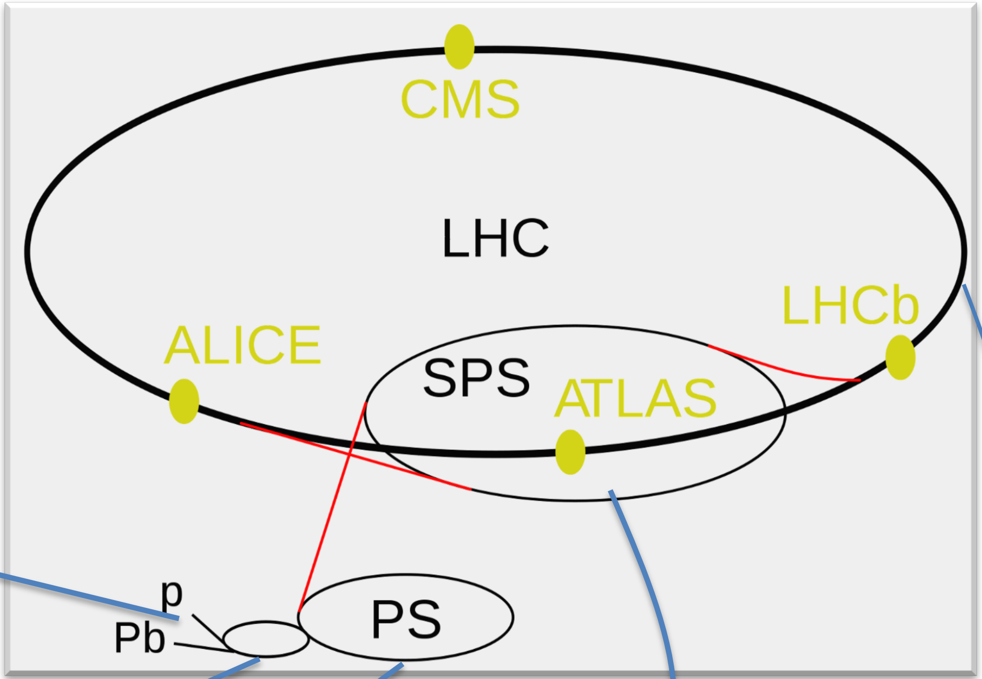
(b)



超导线圈

$$R = \frac{mv}{qB}$$

质子束流是从一罐氢气开始的



Linac 2: 50 MeV

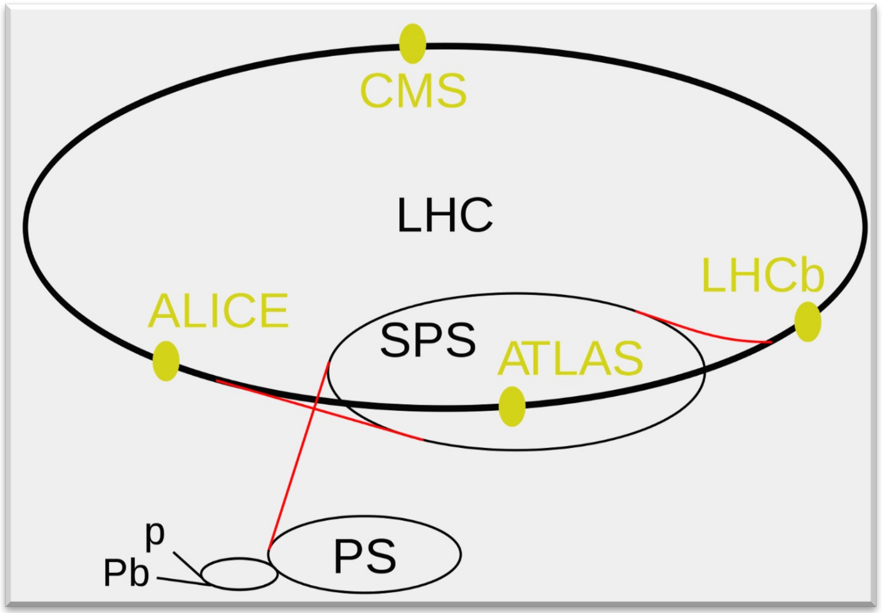
PS Booster: 1.4 GeV

PS: 25 GeV

SPS: 450 GeV

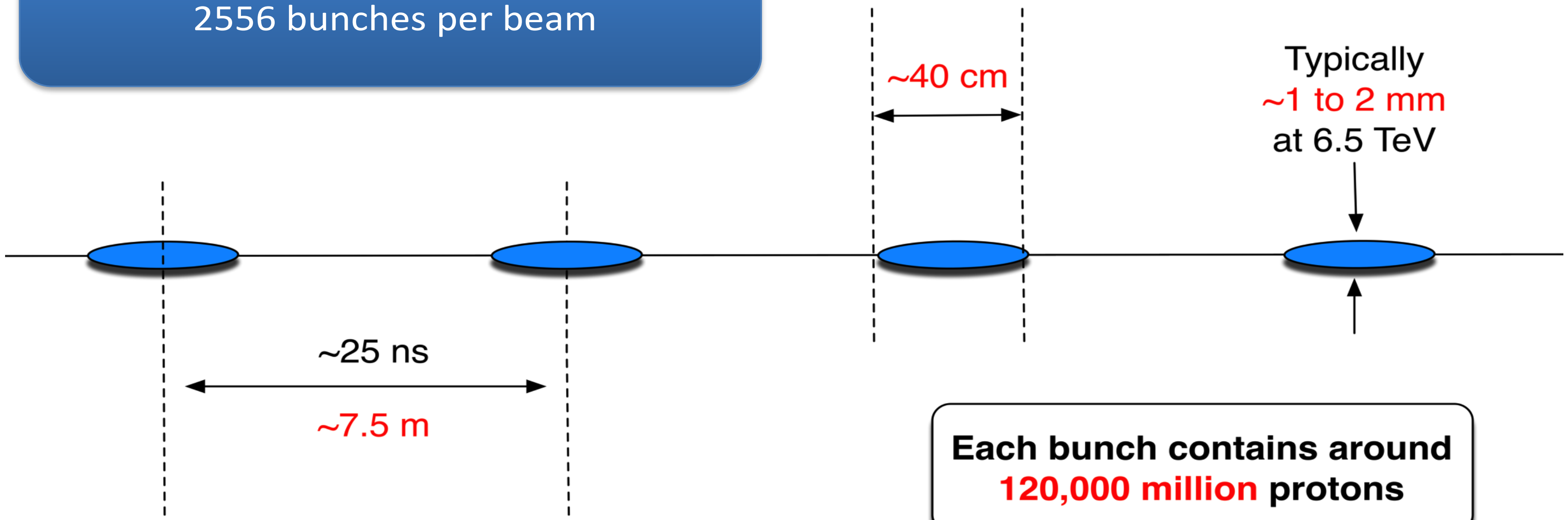
LHC: 13 TeV

1 MeV = 10^6电子伏特
1 GeV = 10^9电子伏特
1 TeV = 10^{12}电子伏特
1电子伏特：单个电子被1伏特的电压加速得到能量

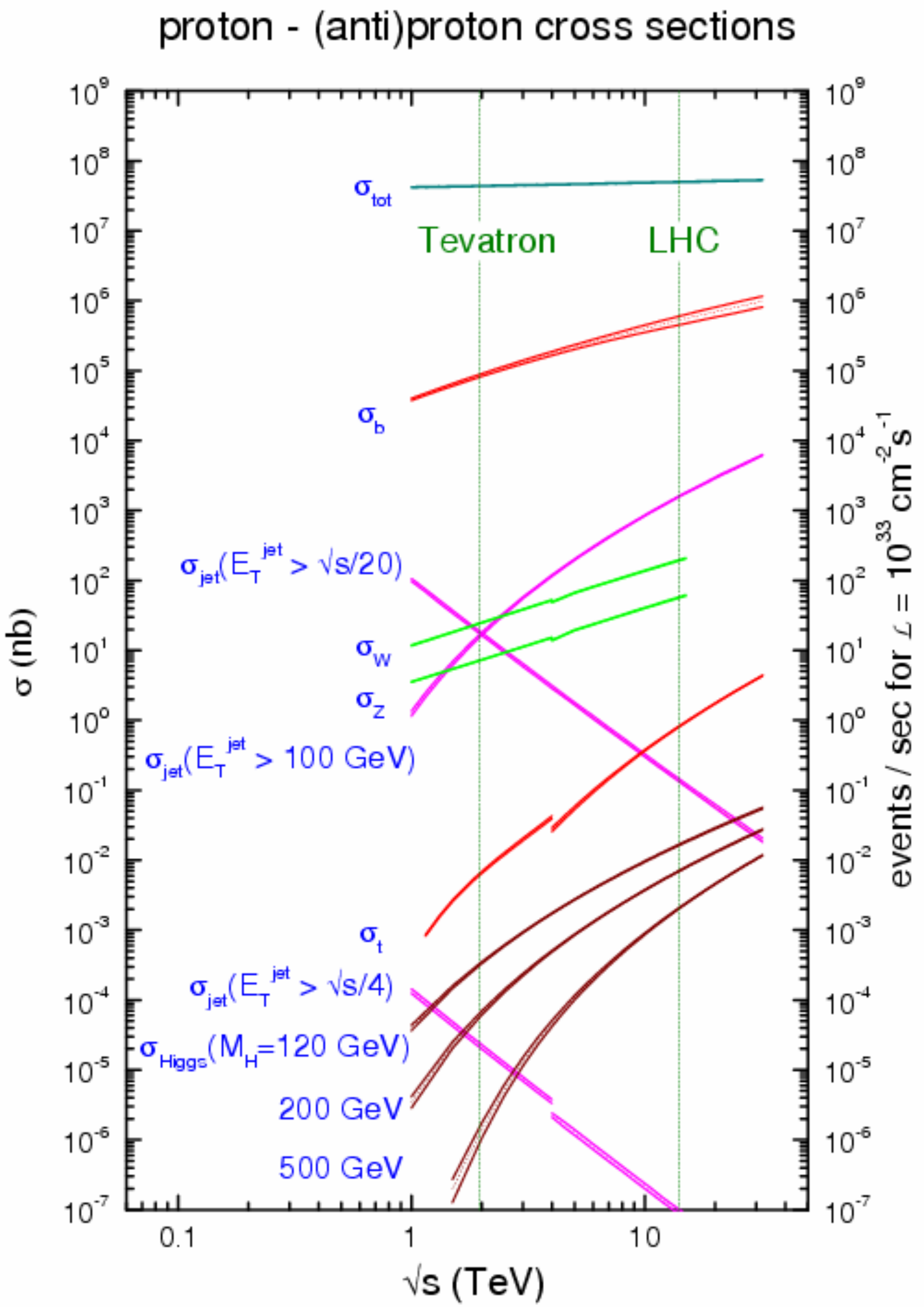


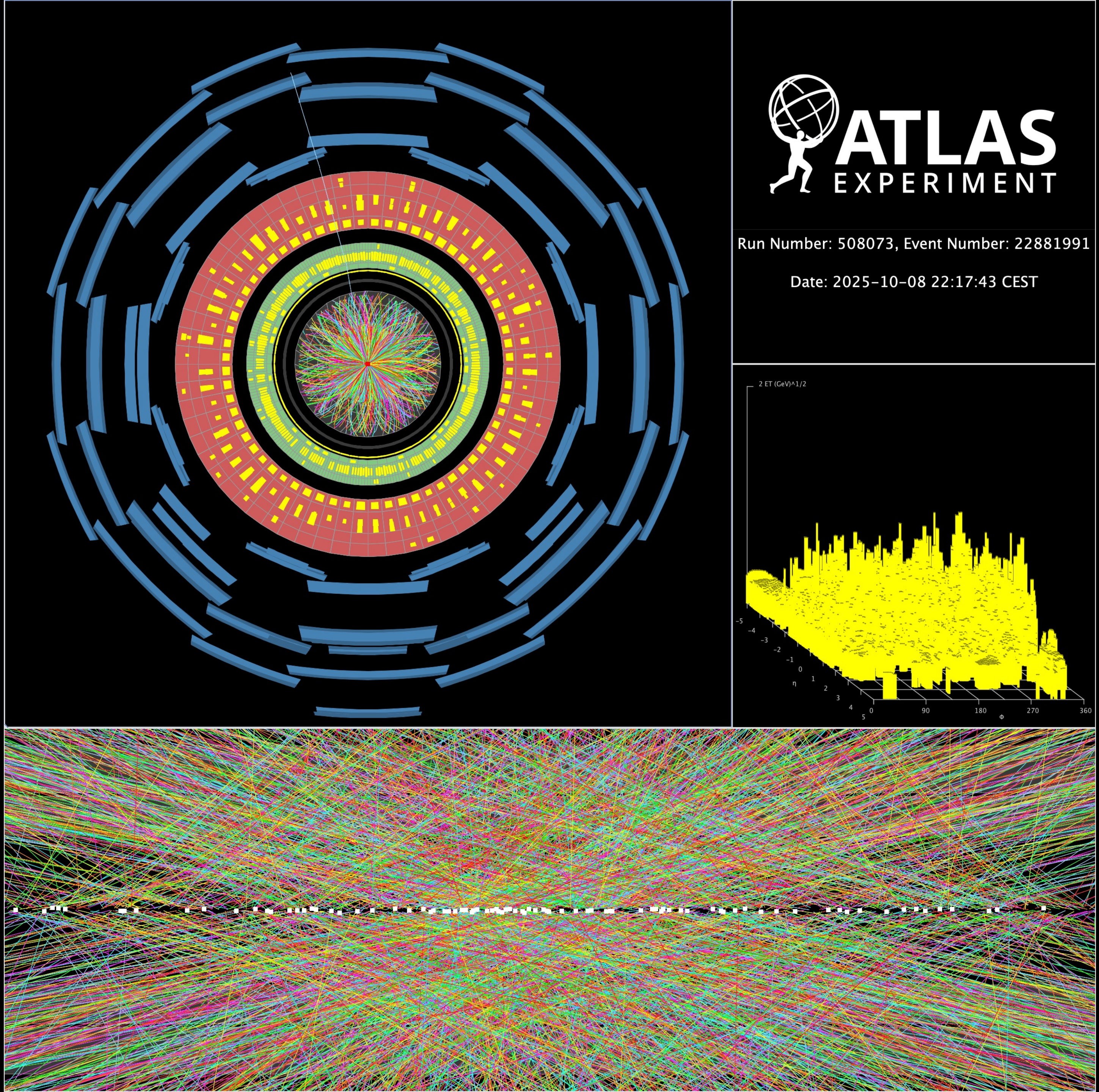
两个束流，每个束流：2808 bunches
每个bunch：1.15×10^{11} 个质子
Bunch之间的时间间隔：25 纳秒（1纳秒=10^{-9}秒）
Bunch的对撞次数：每秒4千万次
一期对撞能量 7/8TeV
二期对撞能量 13TeV
三期对撞能量 13.6TeV

In 2017 the LHC is operating with
2556 bunches per beam



Each bunch contains around
120,000 million protons


proton - (anti)proton cross sections
σ (nb)
events / sec for ℒ = 10^33 cm^-2 s^-1
√s (TeV)
Tevatron
LHC
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σt
σjet(ET jet > √s/4)
σHiggs(MH=120 GeV)
200 GeV
500 GeV
0.1
1
10



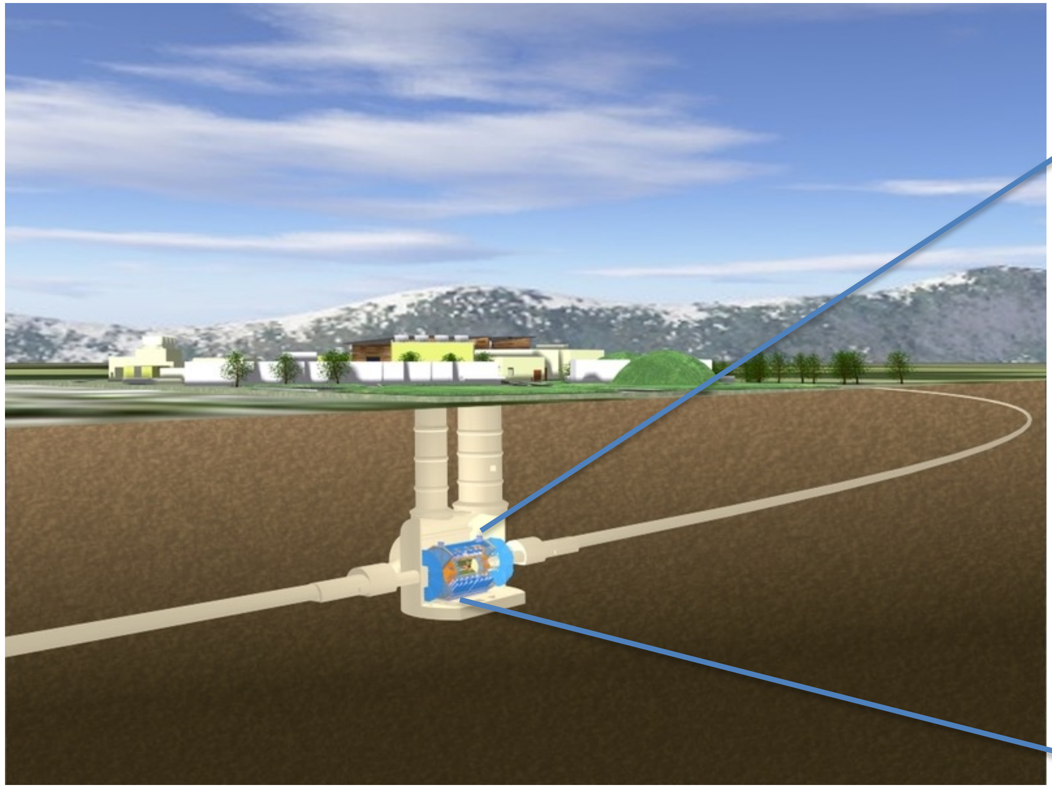
Run number 508073, Event number 22881991

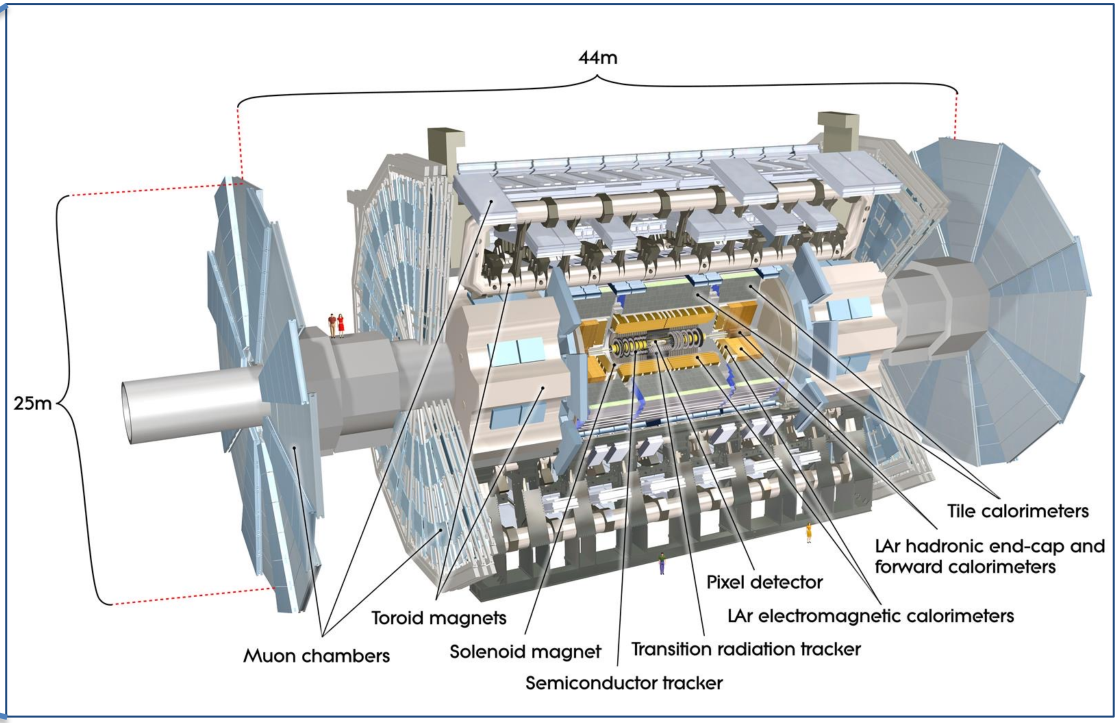
A visualization of an event recorded by the ATLAS experiment (run 508073, event 22881991) on October 8, 2025, when the Large Hadron Collider accelerator was providing proton-proton collisions at 13.6 TeV with a "high-mu" setup.

In a "high-mu" setup, the proton beams in the accelerator are focused and directed to produce a high number of collisions per bunch crossing. The event visualized here was recorded in a collision with an average of 150 proton-proton interactions, and 92 primary vertices were reconstructed.

ATLAS (A Toroidal LHC ApparatuS)

~3000人的合作组

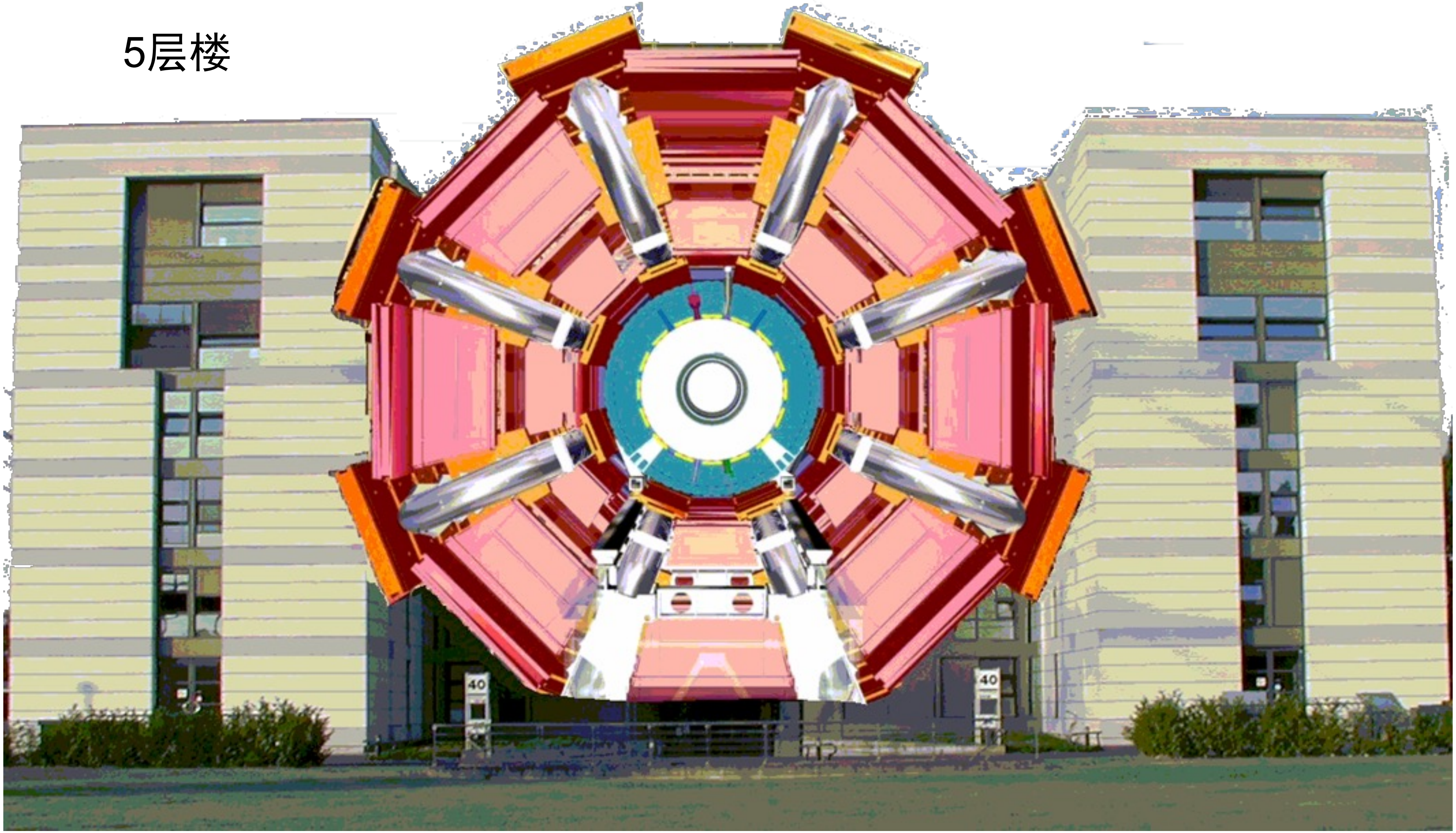




地下大约100米

ATLAS

5层楼



2881位作者

1190 位博士研究生

1304位工程师

5940位活跃的成员

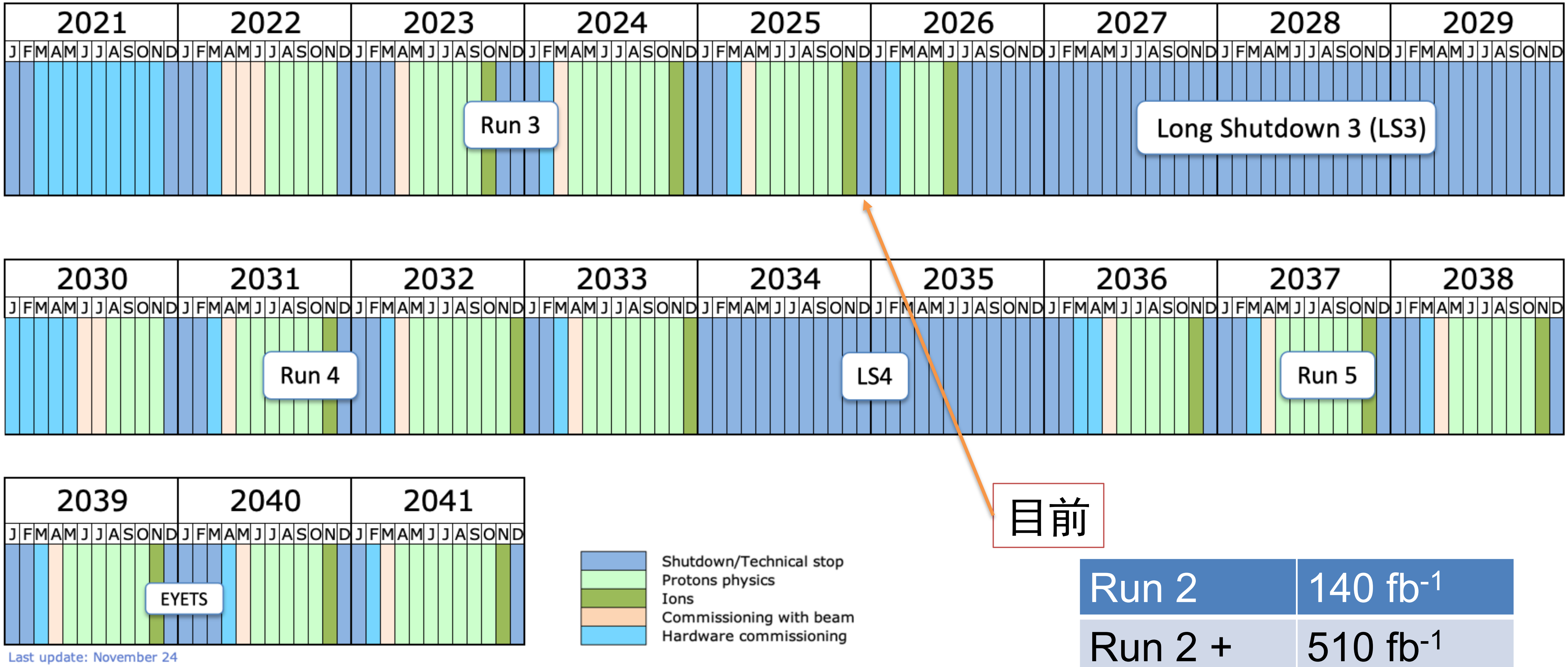
Argentina	Netherlands
Armenia	Norway
Australia	Palestine
Austria	Philippines
Azerbaijan	Poland
Belarus	Portugal
Brazil	Romania
Canada	Russia
Chile	Serbia
China	Slovakia
Colombia	Slovenia
Czech Republic	South Africa
Denmark	Spain
France	Sweden
Georgia	Switzerland
Germany	Taiwan
Greece	Türkiye
Israel	UAE
Italy	UK
Japan	USA
Mongolia	CERN
Morocco	JINR

ATLAS 合作组

ATLAS Collaboration

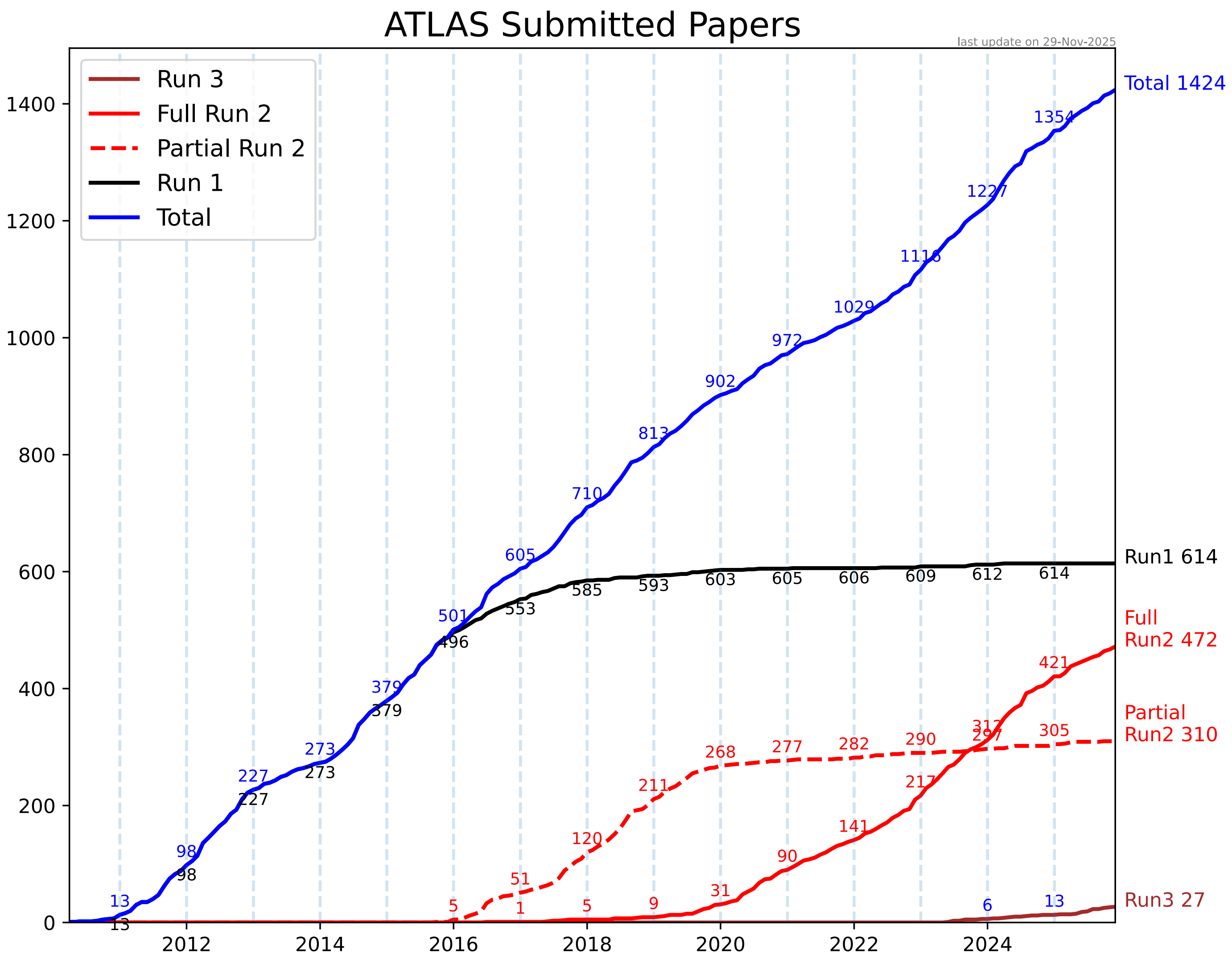
182 institutions (250 institutes) from 42 countries

LHC Schedule



Run 2	140 fb^{-1}
Run 2 + Run 3	510 fb^{-1}

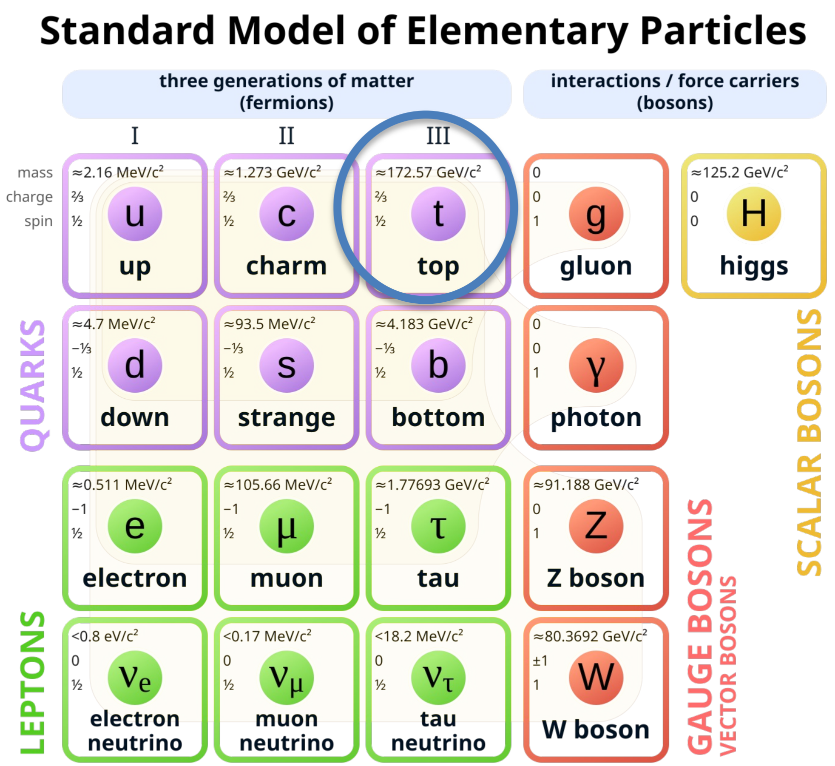
ATLAS实验从LHC运行以来共发表文章1424篇



Top Quark

- Top quark is very special. Heaviest quark in the SM (m_t~172.5 GeV).
- Has largest Yukawa coupling to the Higgs field ($y_t \sim 1$)
- Very short life time → decays before forming any real hadron → access to 'bare' quark

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \text{s}}}$$



- Precision measurements of top quark: important for testing the SM and looking for new physics beyond SM

Top Quark

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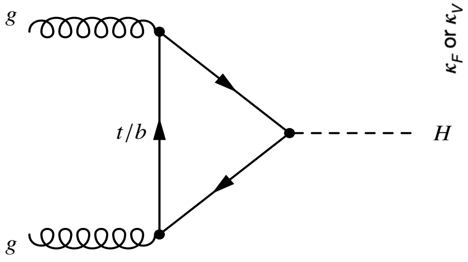
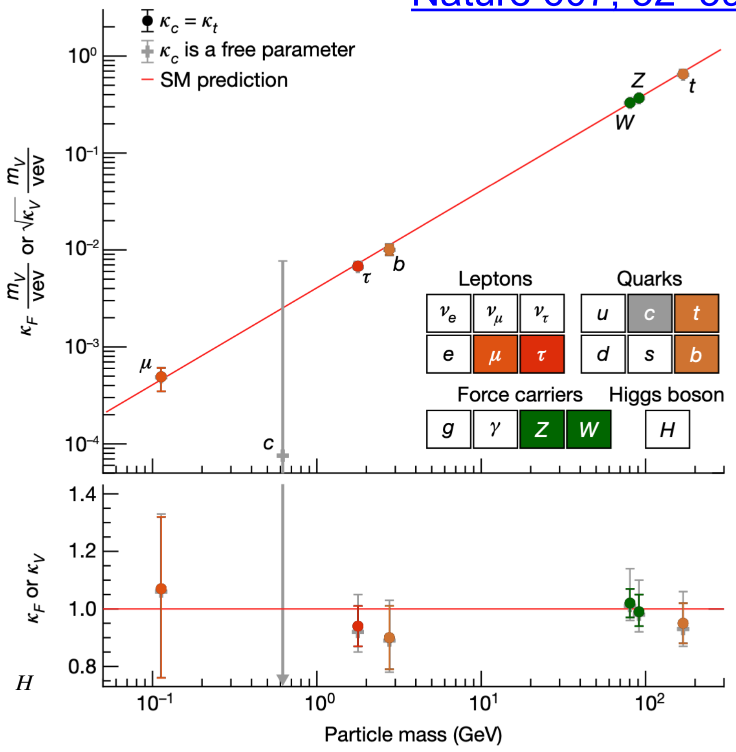


Nature 607, 52–59 (2022)

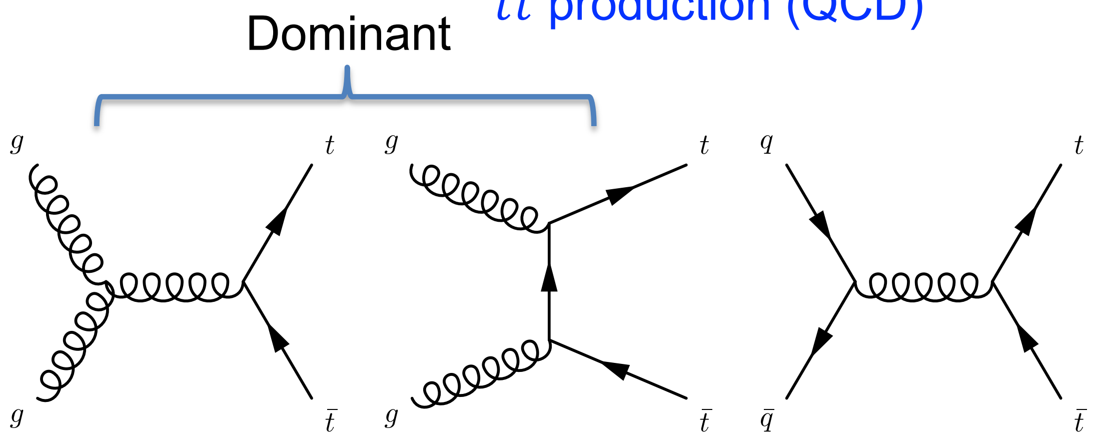


- Precision measurements of top quark: important for testing the SM and looking for new physics beyond SM

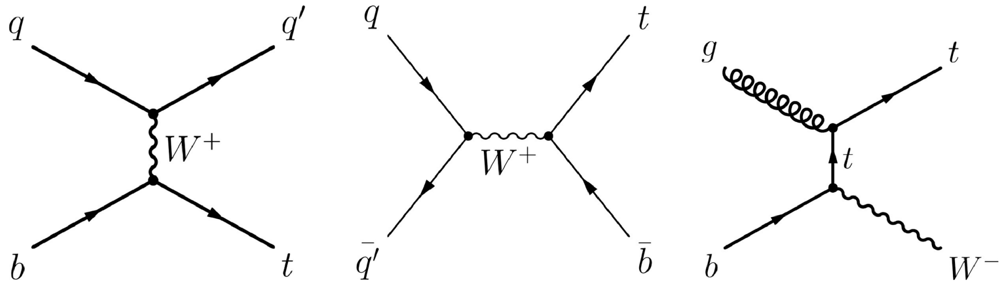
LHC is a top quark factory

- LHC is a $t\bar{t}$ factory
  - $\sigma_{t\bar{t}} = 834$ pb at LHC Run 2
  - 0.83M $t\bar{t}$ events per fb^{-1}
  - Due to the short life time, can measurement $t\bar{t}$ spin correlations
- With those huge amount of $t\bar{t}$ data, ATLAS has carried out precision measurements in top quark physics
- Thanks to the advanced MC generators and high-order QCD/EW calculations

$t\bar{t}$ production (QCD)

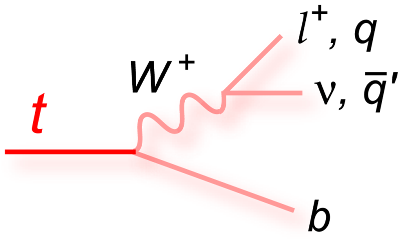


Single top production (EW)



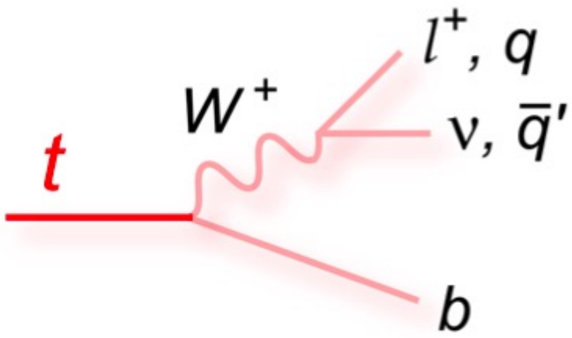
t-channel s-channel tW

Top decays (EW): almost 100% with



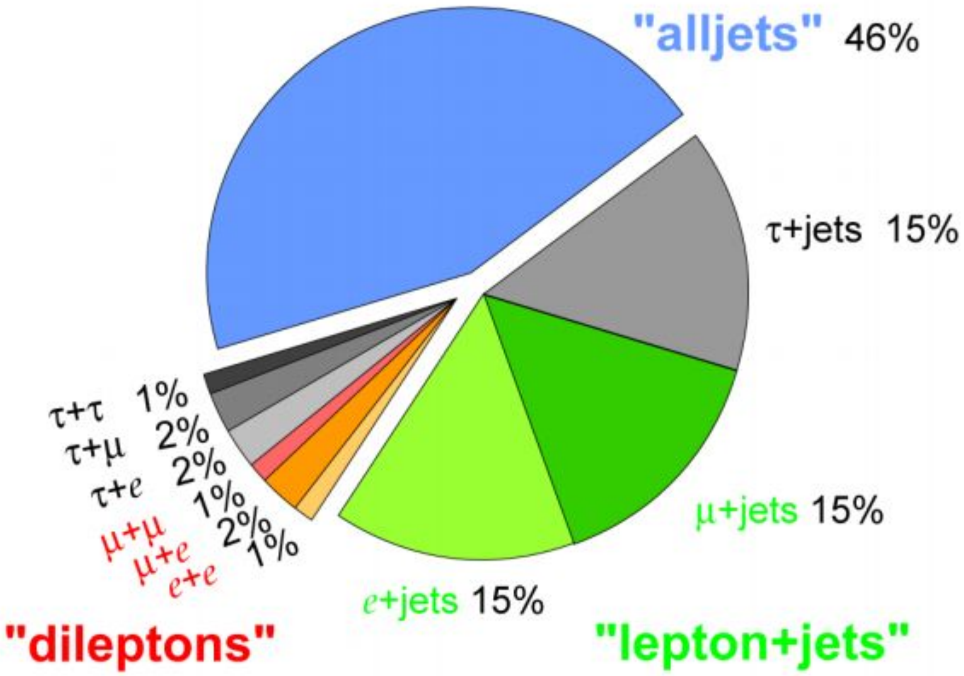
Top Quark Production and Decays at LHC

- Decay (EW)



Complicated decay final states. Almost use all parts of the ATLAS detector

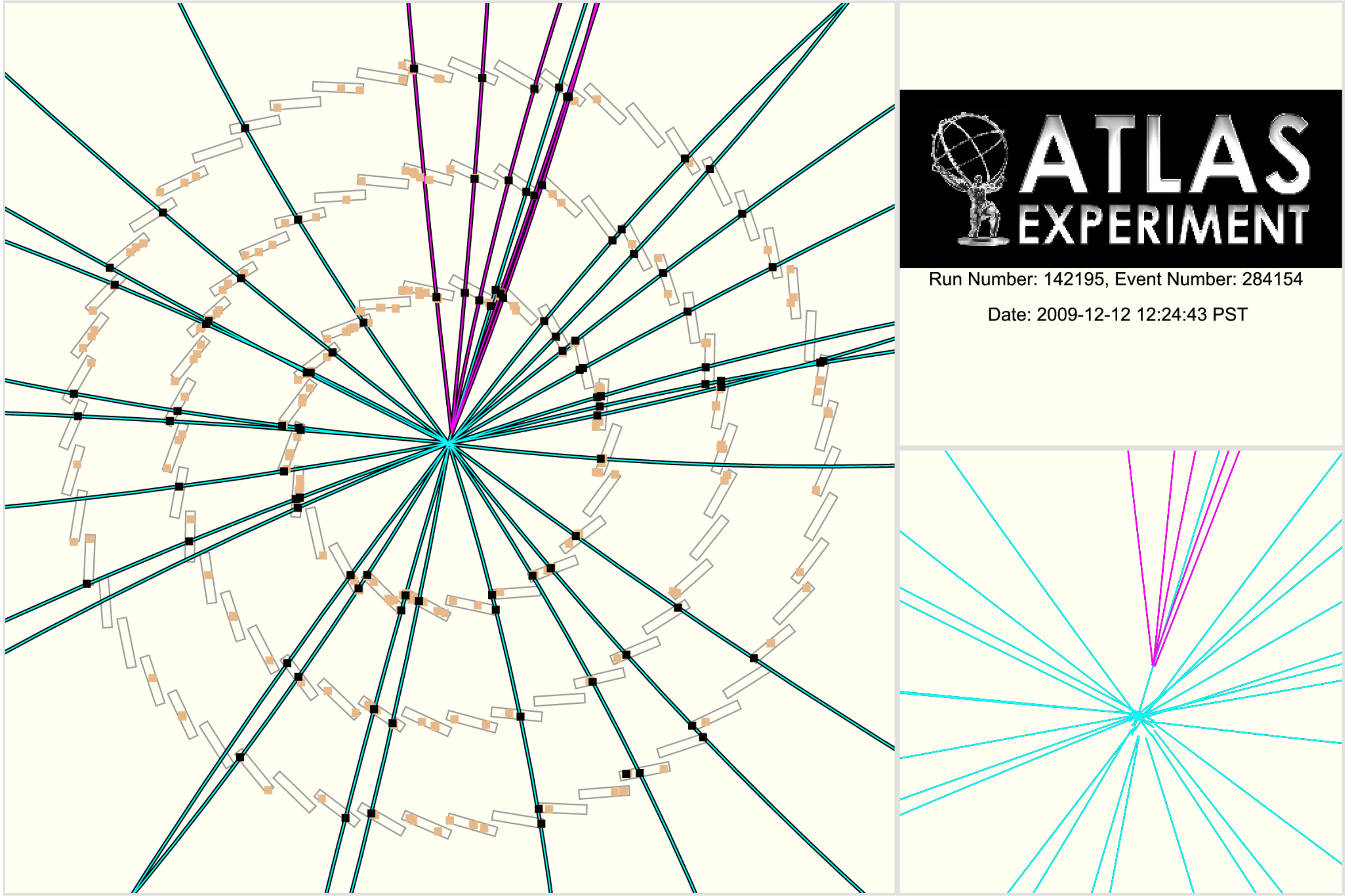
ttbar decay



b-jet

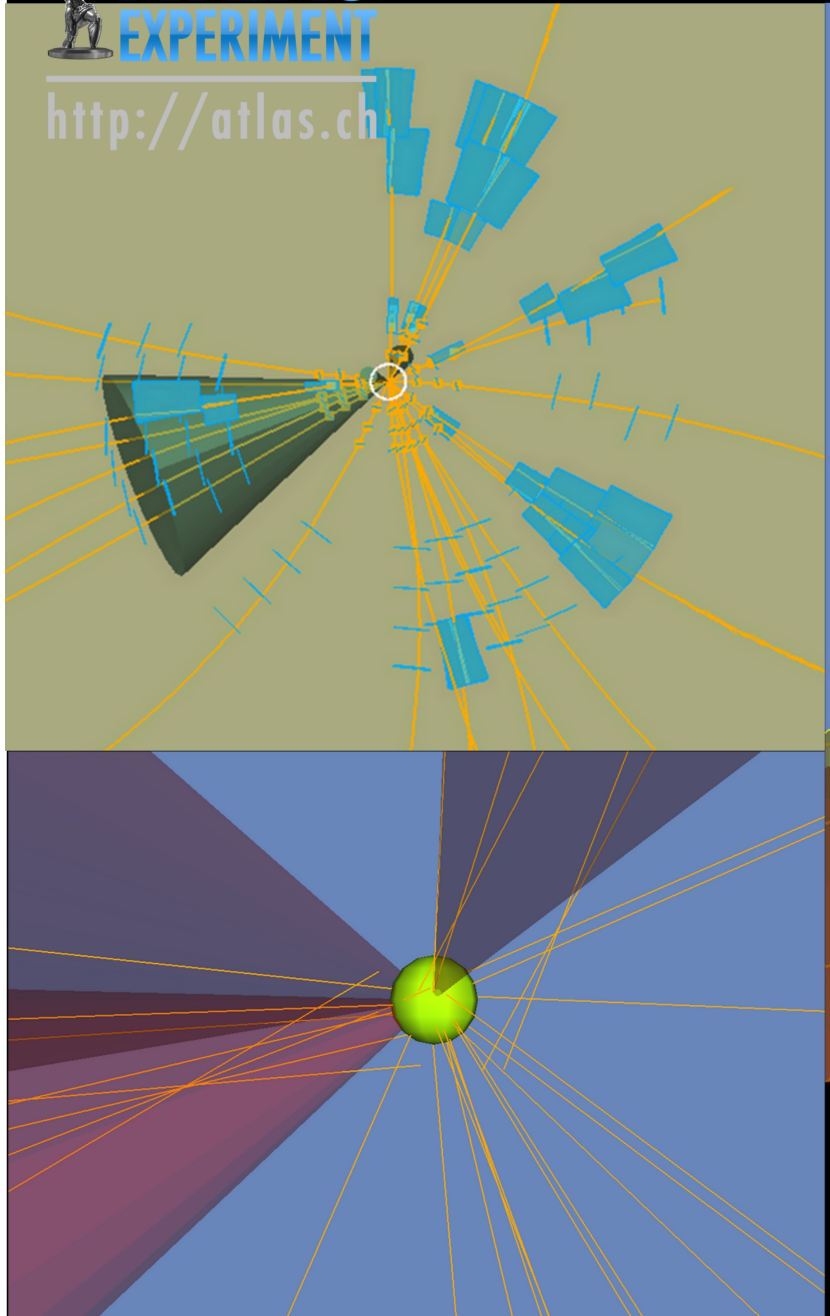
一个50 GeV的B强子
大约在横向飞行3毫米

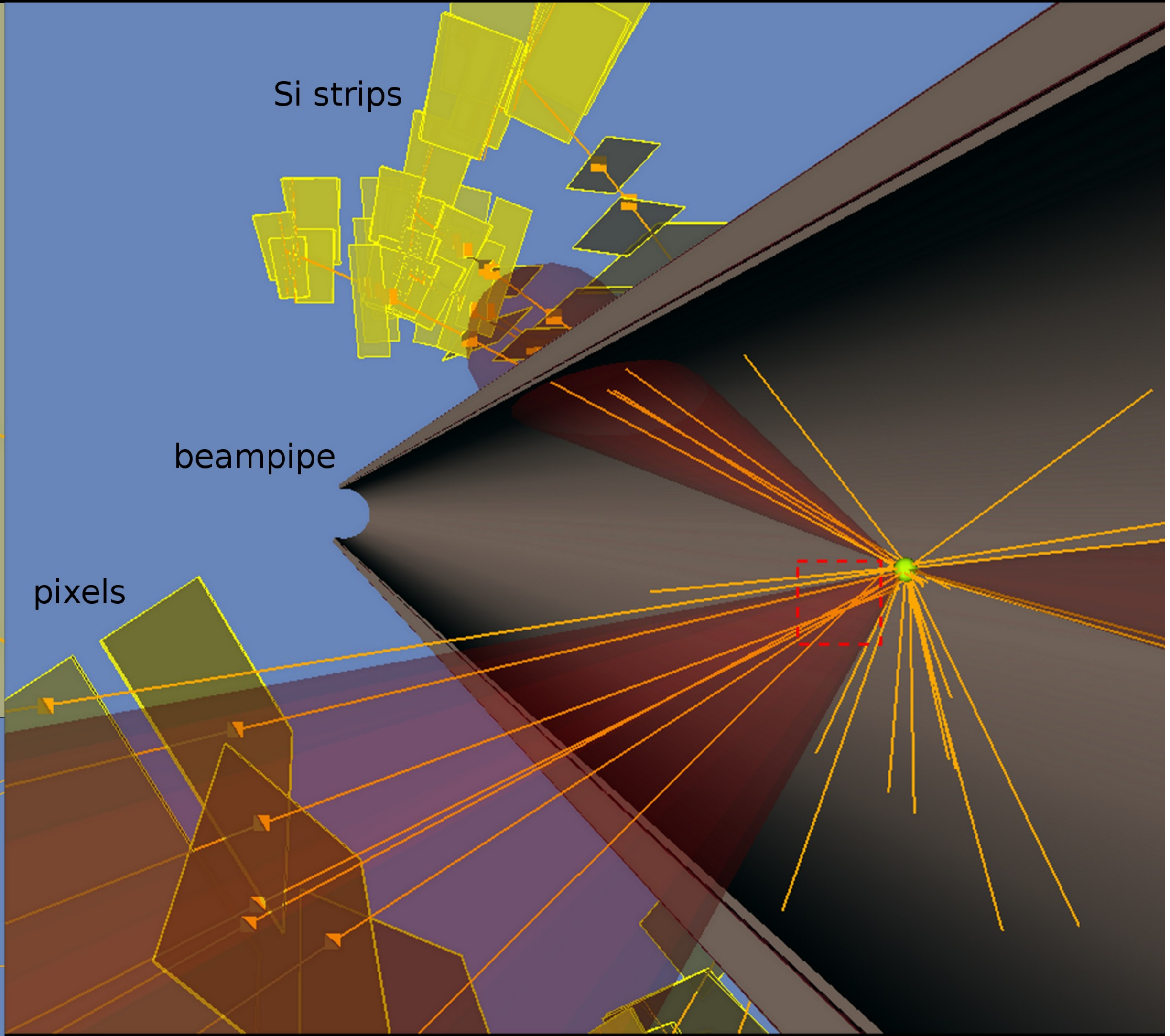
在束流管内衰变。进
入探测器之前



Run 152166
Event 817271

b-tagged jet in 7 TeV collisions





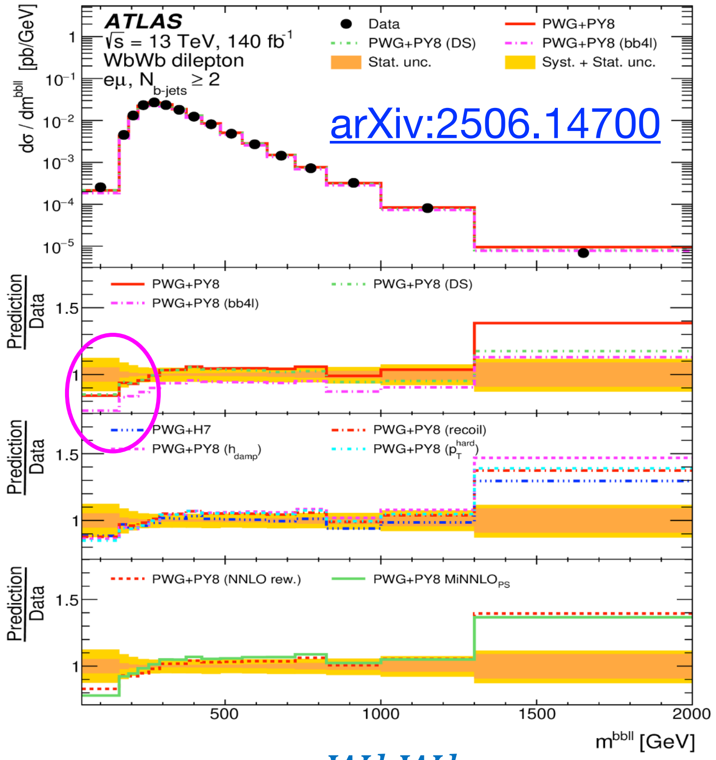
p_T^{jet}=19 GeV (measured at electromagnetic scale)

4 b-tagging quality tracks in the jet

Threshold Region Measurement is Challenging

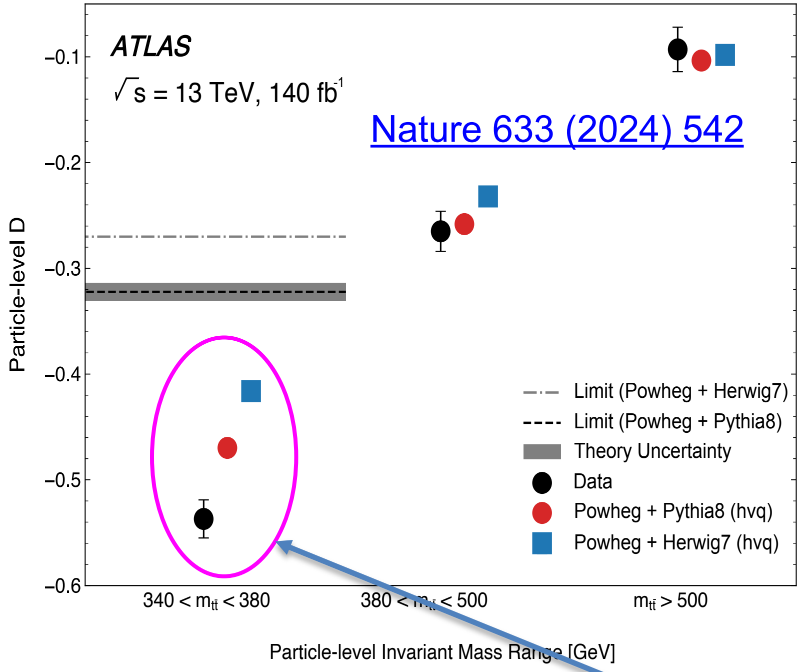
Experimentally very challenging: modelling of $t\bar{t}$ close to threshold region; tiny effect of quasi-bound state

Previous hints



$pp \to WbWb$

First Quantum Entanglement (QE) measurement using $t\bar{t}$ at LHC



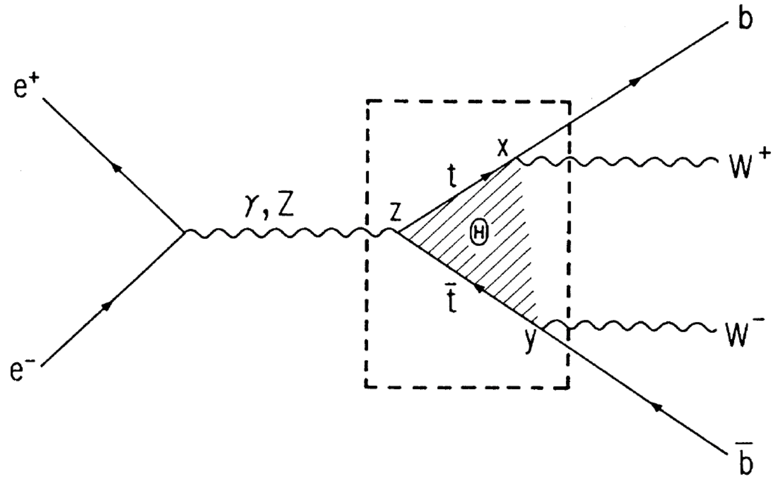
Stronger QE in data than MC.
Missing toponium contributions?

Threshold region has received a lot of attention recently in the context of quantum entanglement

Top quark and $t\bar{t}$ Threshold Region

QCD predicts a quasi-bound state close to the threshold for low momentum top quarks (the prediction was made even before the top quark discovery)

Phys. Rev. D 47 (1993) 56

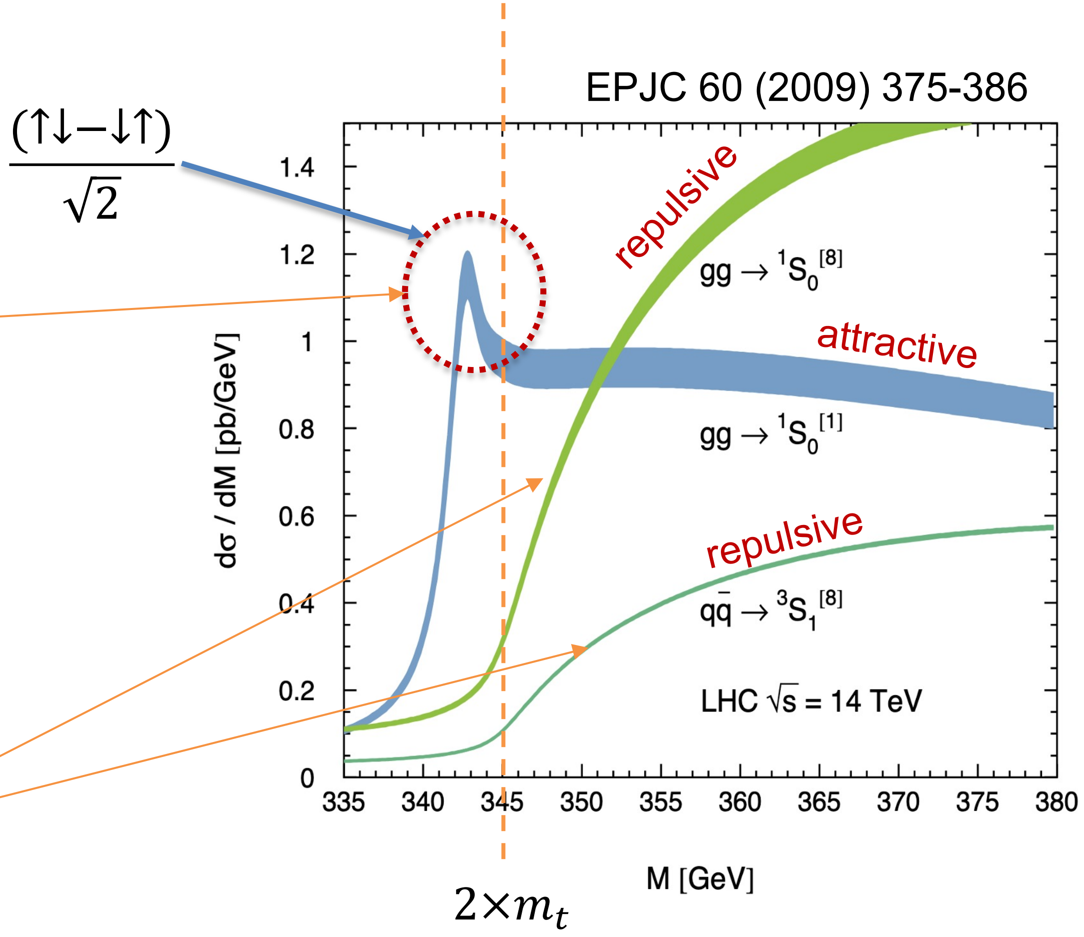


部分理论文章：
V.S. Fadin and V.A. Khoze, JETP Lett. 46 (1987) 525
Y. Sumino *et al.*, Phys. Rev. D 47 (1993) 56
W.-L. Ju *et al.*, JHEP 06 (2020) 158 （浙大杨李林教授团队）

NRQCD Predictions

Color-singlet - attractive
→ Peak below the ttbar threshold
CP-odd / pseudoscalar spin state!

Color-octet - repulsive
→ Suppressed below the tt threshold

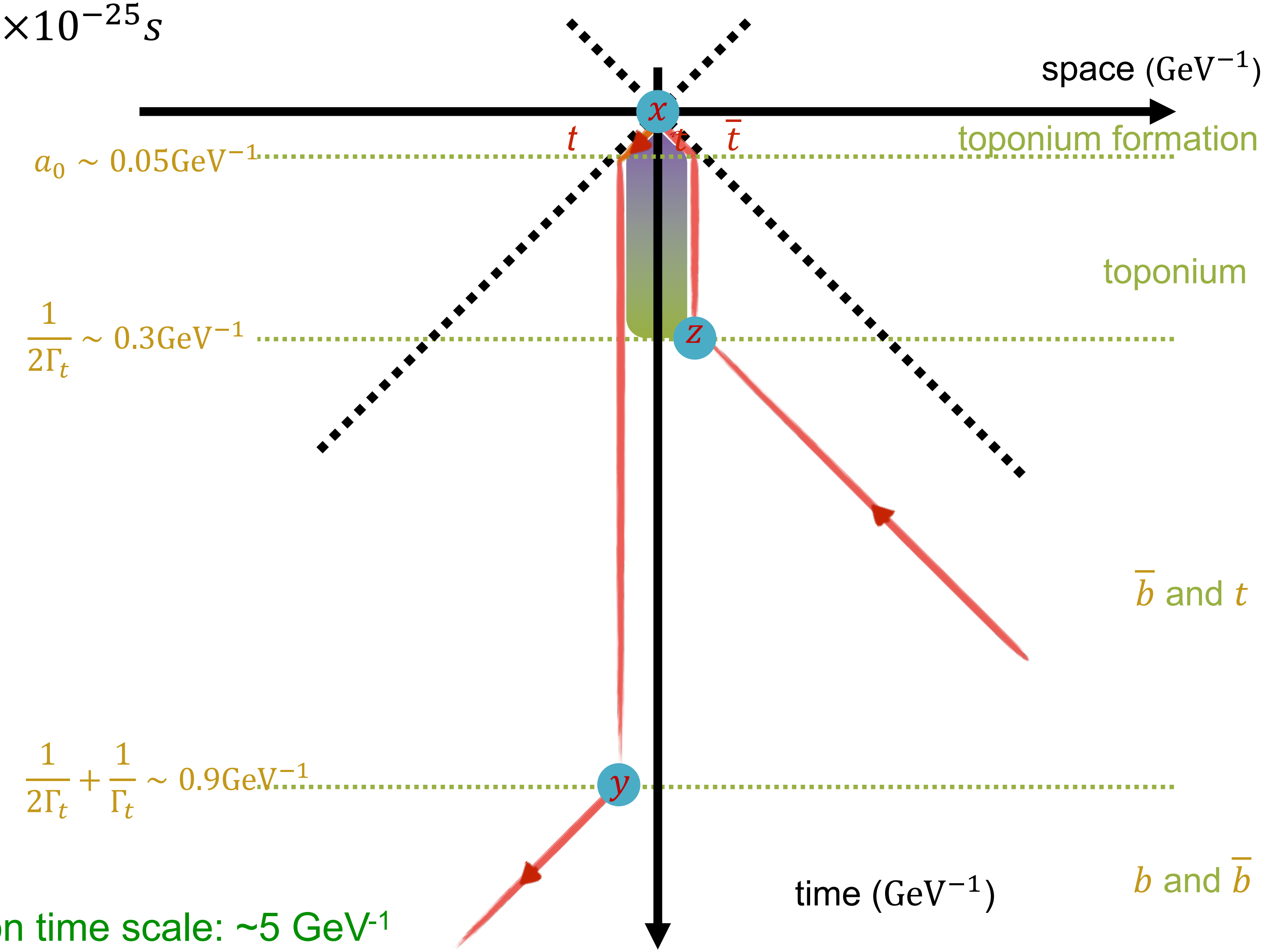


ATLAS Results

Top-antitop production near threshold

$1\ \mathrm{GeV}^{-1} = 6.852\times10^{-25}s$

From B. Fuks



Hadronization time scale: ~5 GeV^{-1}

The toponium Green's function

From B. Fuks

$$K_{abcd}(x,y,z) = \left\langle 0 \middle| T\left\{ t_c(y)\bar{t}_d(z) : \bar{t}_a(x) t_b(x) : \right\} \middle| 0 \right\rangle$$

$$= \frac{(1+\gamma^0)_{ca}}{2} \frac{(1-\gamma^0)_{bd}}{2} \int \mathrm{d}^3 r \Big[K_1\big(y; (z^0, \vec{r})\big)\, K_2(z^0, \vec{r}, \vec{z}; x^0, \vec{x}, \vec{x}) + K_1\big(z; (y^0, \vec{r})\big)\, K_2(y^0, \vec{y}, \vec{r}; x^0, \vec{x}, \vec{x}) \Big]$$

Antitop-decay first

Top-decay first

Non-relativistic spin projection operators

1-particle-state and 2-particle-state propagators

The toponium Green's function

- Solution to the Lippmann-Schwinger equation
  - Fourier transform of the QCD potential
  - S-wave contributions
- To be solved numerically

$$\widetilde{G}(E;p) = \widetilde{G}_0(E;p) + \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \widetilde{V}_{\mathrm{QCD}}(\vec{p}-\vec{q})\, \widetilde{G}(E;q)$$

Free Green's function

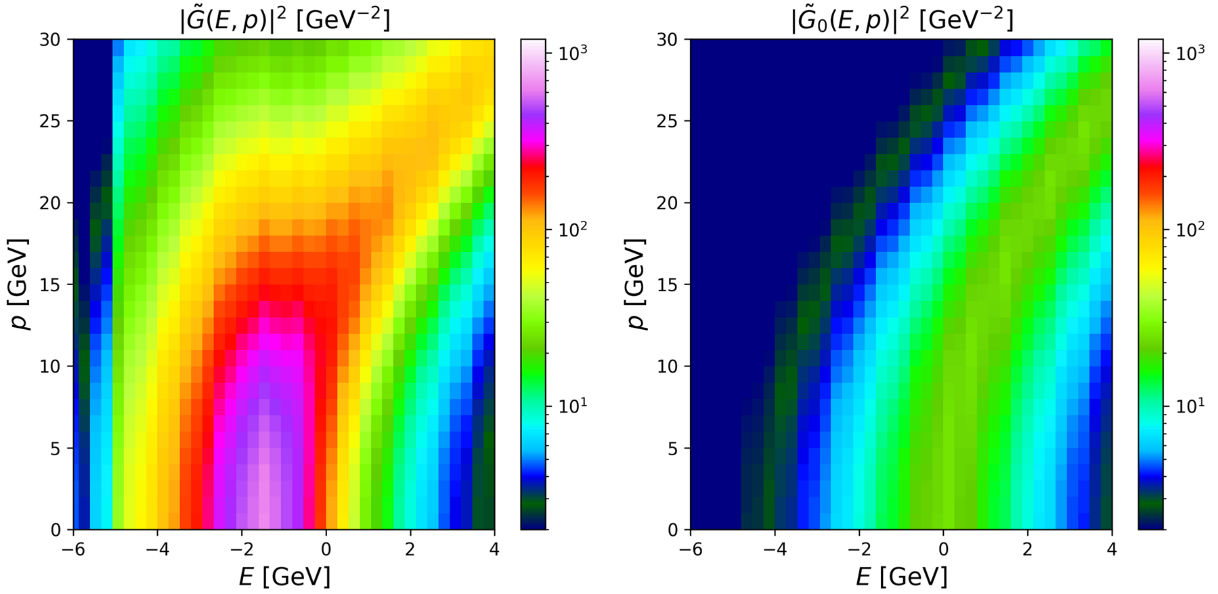
Quasi-bound State from NRQCD

- *S*-wave, color-singlet state with Green's function of non-relativistic (NR) QCD by Eur. Phys. J. C 85 (2025) 157（B. Fuks, K. Hagiwara, 马凯, 郑亚娟）
- Generate $gg \to tt \to b\ell\nu b\ell\nu$ with MG5_aMC. Spin correlations included
- Reweight matrix element with QCD Green's functions

$$|\mathcal{M}|^2 \quad \rightarrow \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E;\, p^*)}{\widetilde{G}_0(E;\, p^*)} \right|^2$$

$\tilde{G}$: Green's function considering QCD potential

$\tilde{G}_0$: Free Green's function



This model includes NRQCD calculations. More complete w.r.t. previous simplified models (using scalar/pseudoscalar as an effective model)

ATLAS Event Selections

Target for dilepton channel $tt \rightarrow b\ell\nu b\ell\nu$

SR: Signal Region; CR: Control Region

140 fb^{-1} LHC
Run 2 pp data

SRs	CR-Z	CR-Fakes
$= 2\ell$ with $p_{\mathrm{T}}(\ell) \geq 10$ GeV ≥ 1 trigger-matched lepton with $p_{\mathrm{T}} \geq 25/27/28$ GeV ≥ 2 jets with $p_{\mathrm{T}} \geq 25$ GeV ≥ 1 b-tagged jet (70% efficiency WP) $m_{\ell\ell} \geq 15$ GeV $m_{t\bar{t}} \leq 500$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}} \geq 60$ GeV for OSSF events		—
$\ell^{\pm}\ell'^{\mp}$ $\lvert m_{\ell\ell} - m_Z \rvert \geq 10$ GeV	$e^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}$ $\lvert m_{\ell\ell} - m_Z \rvert \leq 10$ GeV	$\ell^{\pm}\ell'^{\pm}$ $\lvert m_{\ell\ell} - m_Z \rvert \geq 10$ GeV

OSSF: opposite-sign, same-flavor

CRs are for correcting Z+jets and Fakes normalization in fit

Background Modelling

Extremely challenging measurement: need precise modelling of the $t\bar{t}$ threshold region

- $t\bar{t}$: main background. Powheg v2 hvq + Pythia8, using narrow-width approximation (NWA), with approximate spin correlation
  - 2D reweighting in (cosθ*, M($t\bar{t}$)) to NNLO QCD (from MATRIX) and NLO EW (HATHOR)
  - θ*: angle between the momentum of the top quark in the $t\bar{t}$ center-of-mass frame and the momentum of the $t\bar{t}$ system in the lab. frame
- $t\bar{t}$: alternative MC sample (for syst.), Powheg v2 bb4l + Pythia8
  - Simulate $pp \rightarrow b\ell\nu b\ell\nu$ including off-shell, non-resonant contributions, and exact spin correlations at NLO

Advanced MC generators and state-of-art high-order QCD/EW calculations play crucial rules in this search

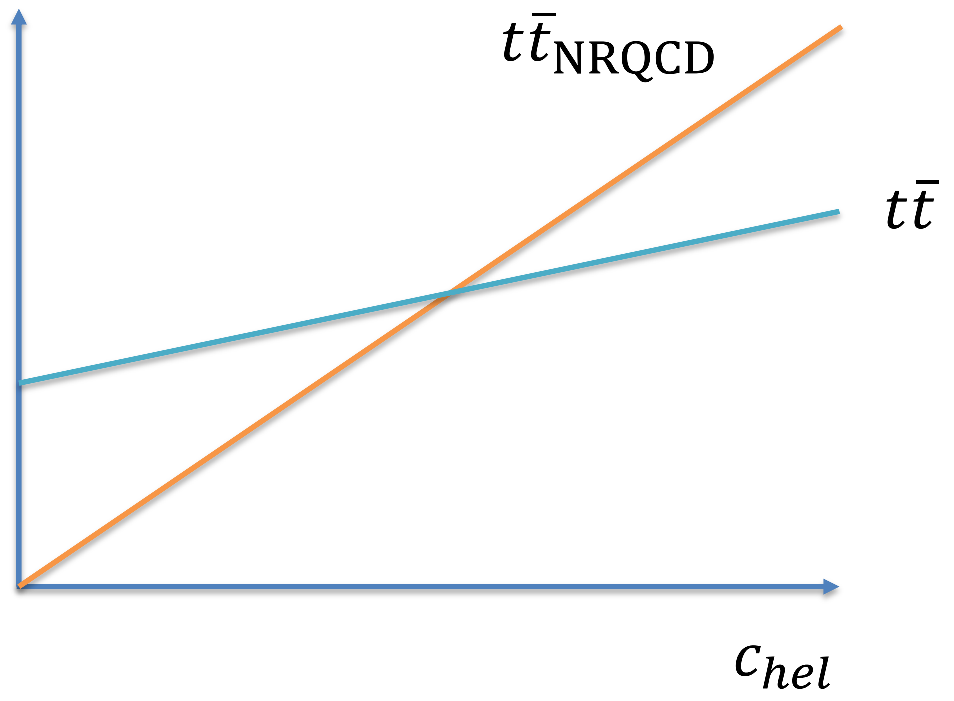
Event Categorization

SR events are categorized into 9 regions based on two observables: c_{hel} and c_{han}

$$c_{hel} = \vec{\ell}_+ \cdot \vec{\ell}_- \, ,$$

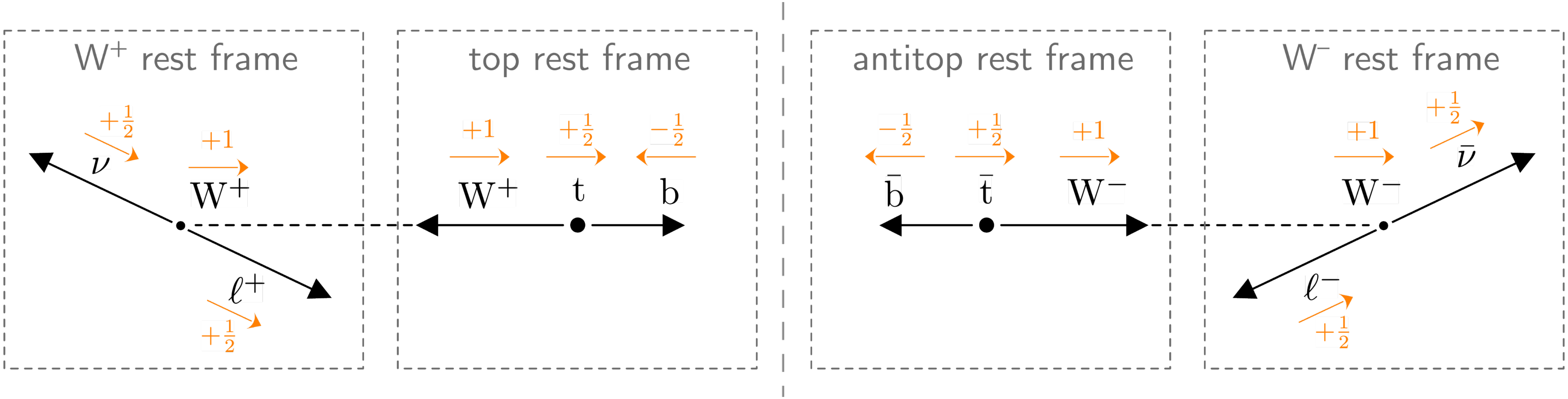
where the $\vec{\ell}_\pm$ are the lepton directions in $t\bar{t}$ center-of-mass frame, and then in turn boosted into t and $\bar{t}$ frames. This distribution has a maximum slope for a spin-singlet state

c_{han}: flip the $\vec{\ell}$ in t direction. This distribution has a maximum slope for a spin-triplet state



c_{hel} is useful to separate pseudoscalar from other contributions

$t\bar{t}$ Spin Correlation



- Transfer of spin information to leptons due to parity violation of weak interaction + conservation of angular momentum
- Antilepton emitted preferably parallel to parent top quark spin
- Lepton emitted preferably antiparallel to parent antitop quark spin

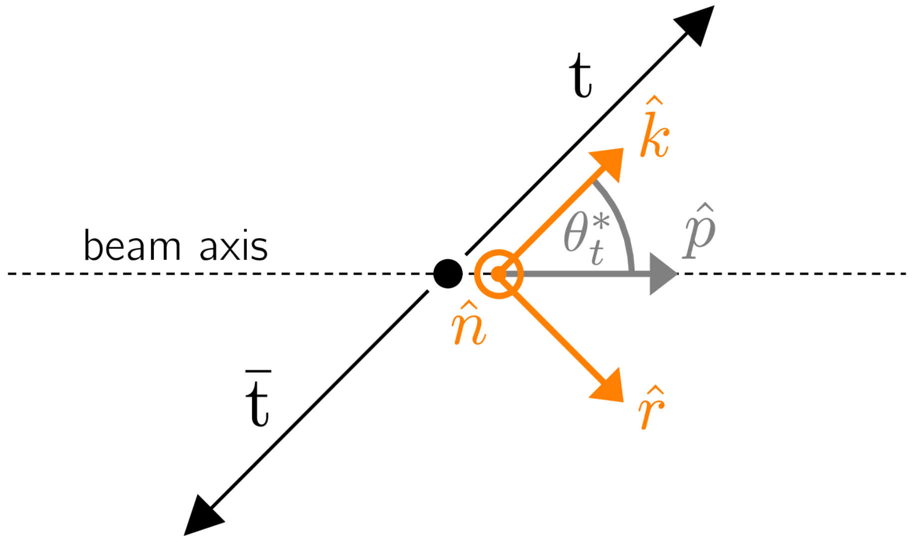
Spin Density Matrix

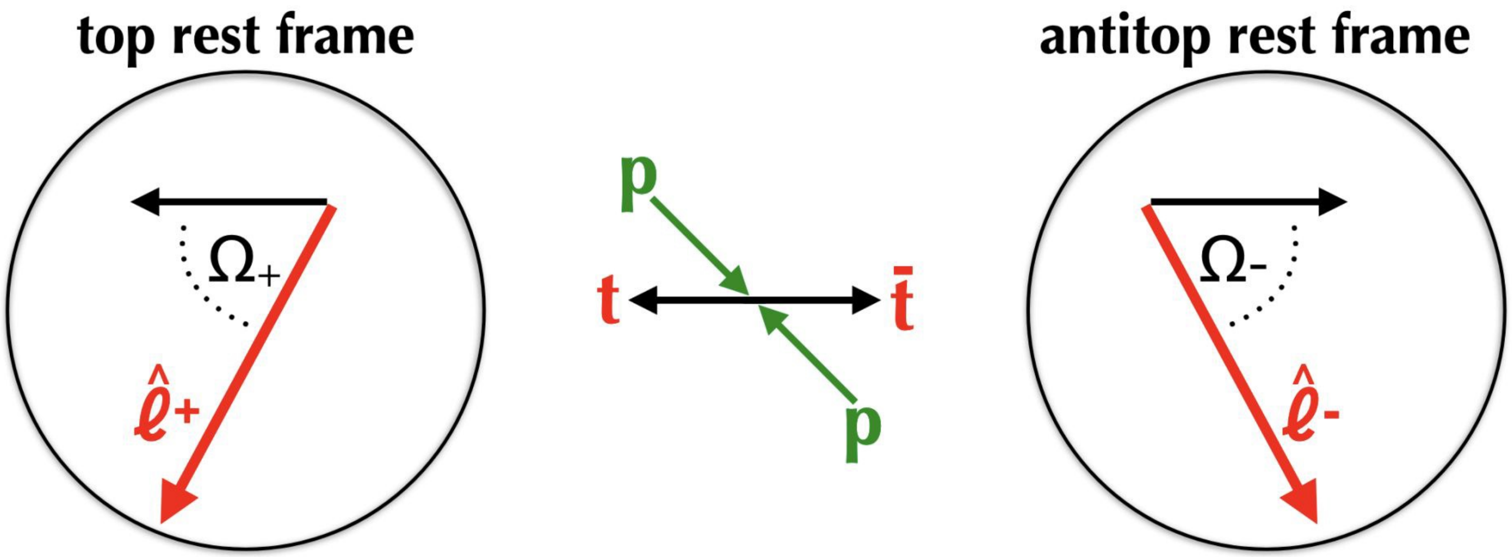
- tt spin state is encoded in spin density matrix:

$$\mathbf{R} = A + B_i\sigma_i + \overline{B}_i\overline{\sigma}_i + \sigma_i C_{ij}\overline{\sigma}_j$$

cross section — polarization vectors — correlation matrix

- Choose helicity basis $\{\hat{k}, \hat{r}, \hat{n}\}$:
  - $\hat{k}$: direction of flight of the top quark
  - $\hat{r}$ and $\hat{n}$: orthogonal to $\hat{k}$





$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$

$$c_{\rm hel} = \hat{\ell}_t^+ \cdot \hat{\ell}_{\bar{t}}^- = +(\hat{\ell}_t^+)_k(\hat{\ell}_{\bar{t}}^-)_k + (\hat{\ell}_t^+)_r(\hat{\ell}_{\bar{t}}^-)_r + (\hat{\ell}_t^+)_n(\hat{\ell}_{\bar{t}}^-)_n$$

$$c_{\rm han} = -(\hat{\ell}_t^+)_k(\hat{\ell}_{\bar{t}}^-)_k + (\hat{\ell}_t^+)_r(\hat{\ell}_{\bar{t}}^-)_r + (\hat{\ell}_t^+)_n(\hat{\ell}_{\bar{t}}^-)_n$$

Event Categorization and Fitting

	$-1 < c_{hel} < -\frac{1}{3}$	$-\frac{1}{3} < c_{hel} < \frac{1}{3}$	$\frac{1}{3} < c_{hel} < 1$
$-1 < c_{han} < -\frac{1}{3}$	SR1	SR2	SR3
$-\frac{1}{3} < c_{han} < \frac{1}{3}$	SR4	SR5	SR6
$\frac{1}{3} < c_{han} < 1$	SR7	SR8	SR9

CR-Fakes ee	CR-Fakes $e\mu$	CR-Fakes $\mu\mu$	CR-Z

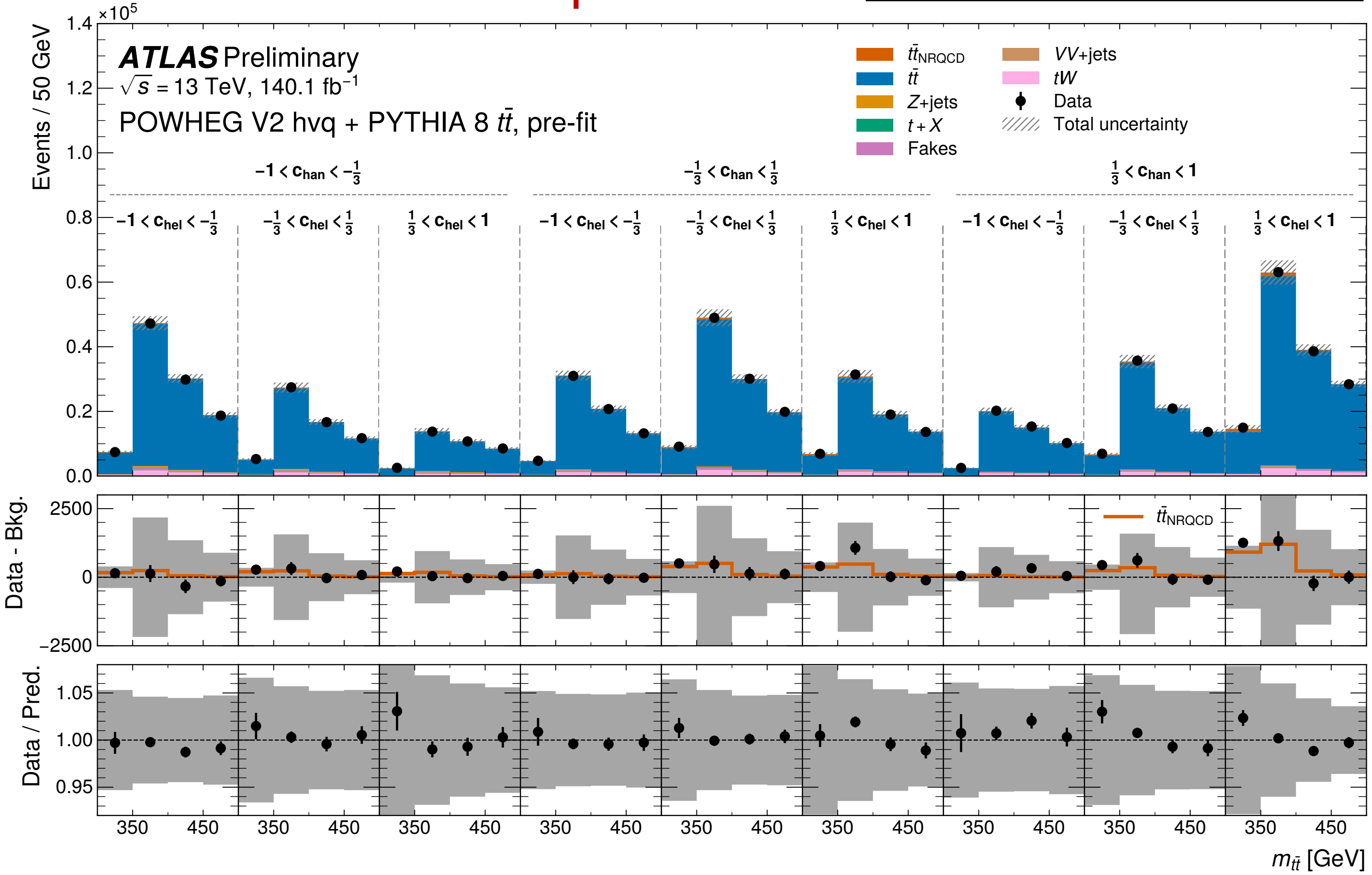
Simultaneous fitting to $m_{t\bar{t}}$ with 13 categories with profile likelihood method

Background Estimations

- $t\bar{t}$: with a free-floating scale factor (SF); tW: estimation from MC
- Z+jets: get some contributions from Z$\rightarrow\tau\tau$. Use the CR-Z to normalize the Z+b process

Pre-fit plots

ATLAS-CONF-2025-008



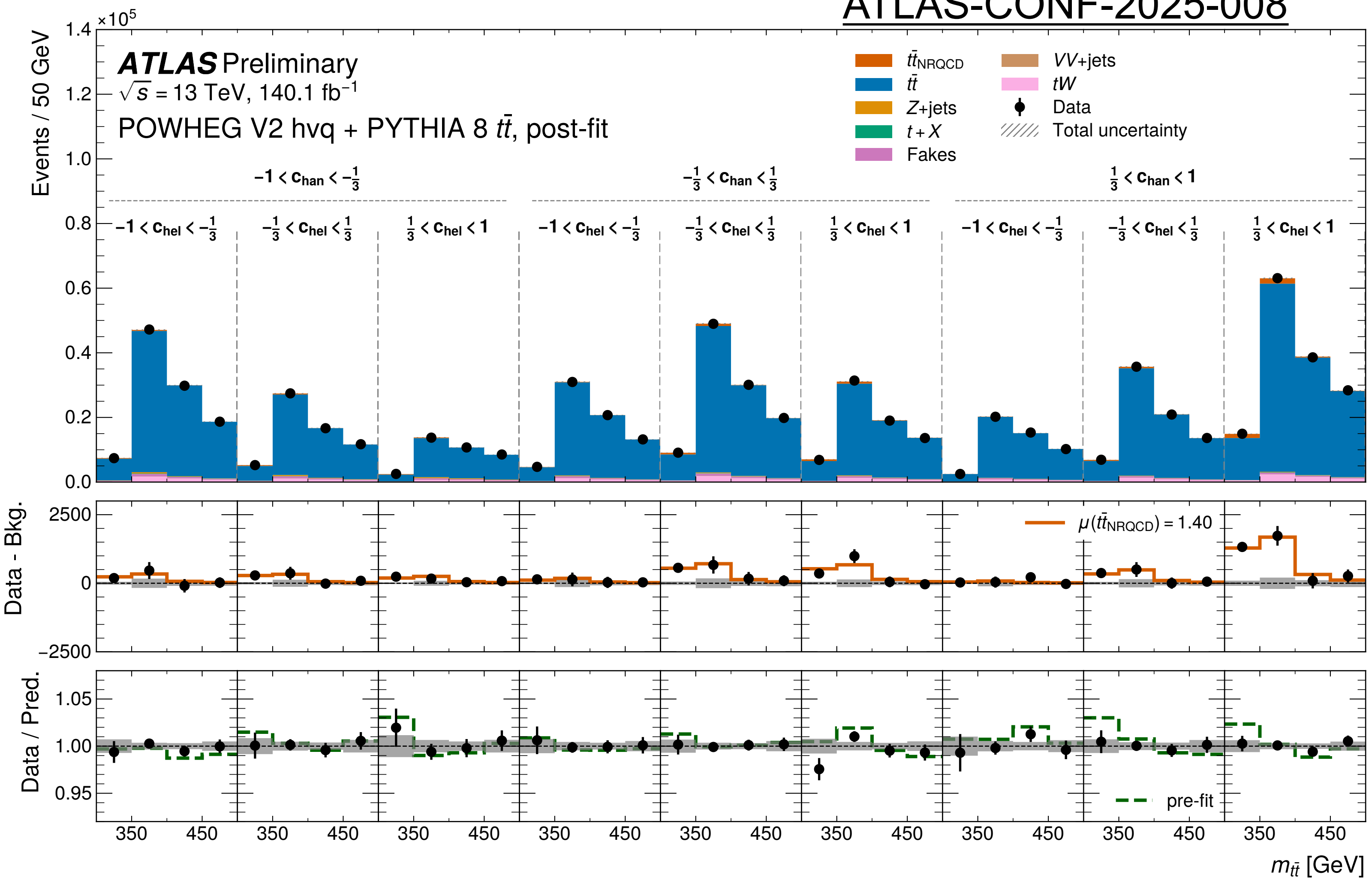
- fake / non-prompt leptons: Fakes represent 1.5% of SR yields. Data-driven estimation with 3 CR-Fakes

Results: baseline $t\bar{t}$ + quasi-bound state (NRQCD)

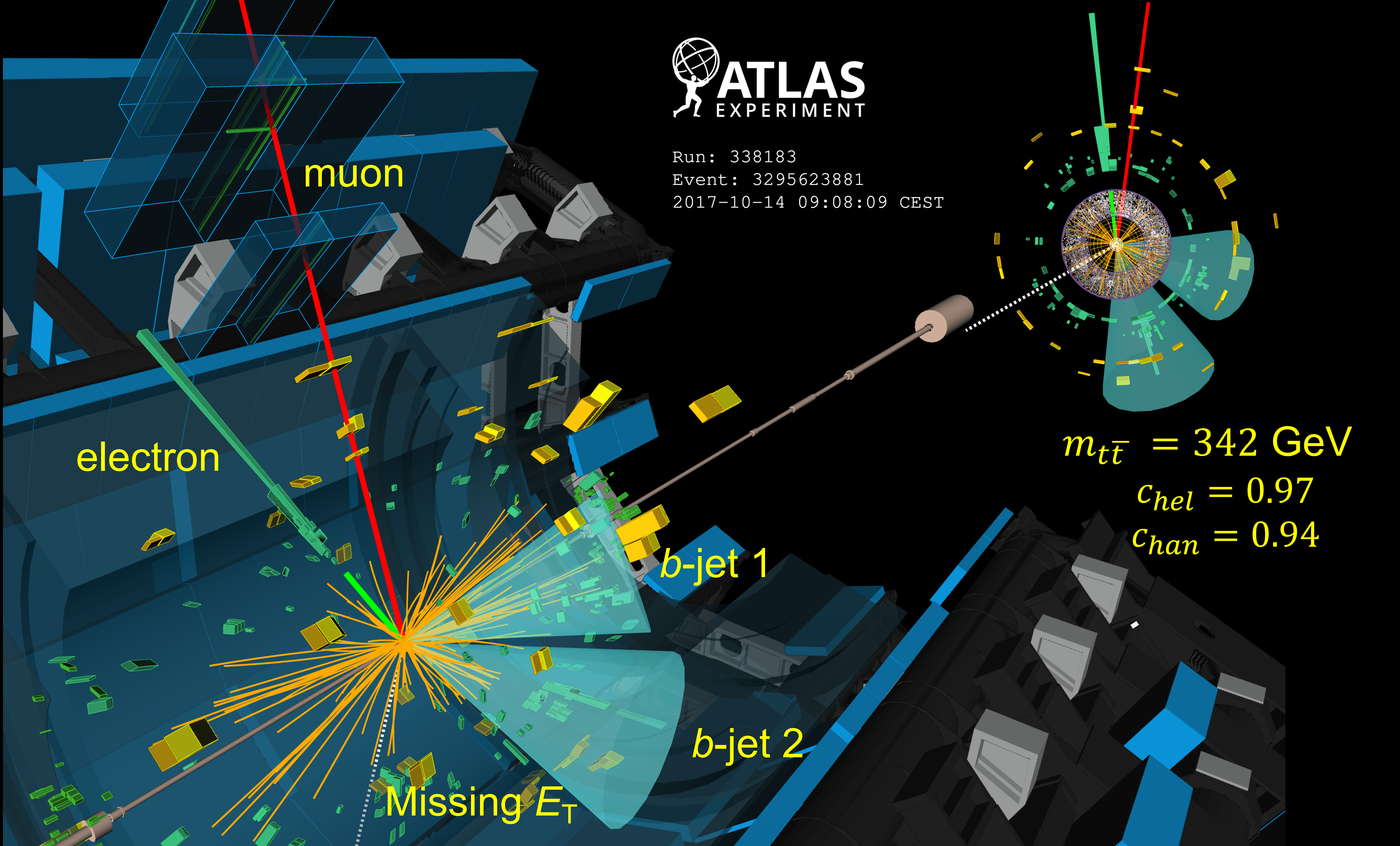
ATLAS-CONF-2025-008

Observed (expected) significance: 7.7σ (5.7σ)

Goodness-of-Fit: 0.93



$$\sigma(t\bar{t}_{\mathrm{NRQCD}}) = 9.0 \pm 1.3 \text{ pb} = 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb}$$



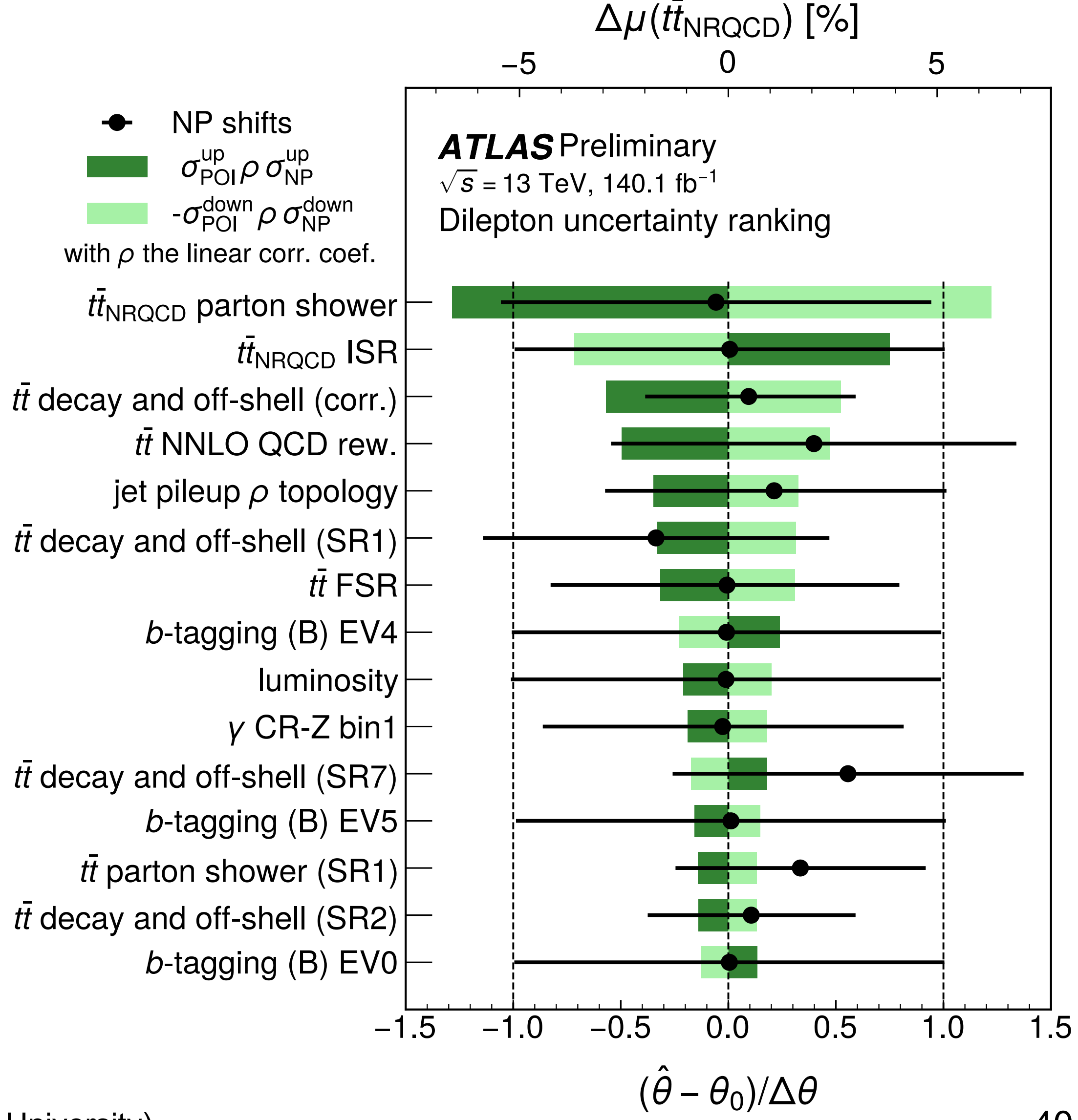
ATLAS
EXPERIMENT
Run: 338183
Event: 3295623881
2017-10-14 09:08:09 CEST
muon
electron
b-jet 1
b-jet 2
Missing E_T
$m_{t\bar{t}} = 342$ GeV
$c_{hel} = 0.97$
$c_{han} = 0.94$

Impacts of Systematics

- Quasi-bound state modelling: Parton shower [Herwig7]
- $t\bar{t}$ decay and off-shell [comparison to bb4l]
- NNLO QCD rew.: NNLO QCD scale variations

- No strong pulls or constraints
- Largest effects from toponium modelling and off-shell effect modelling

ATLAS-CONF-2025-008

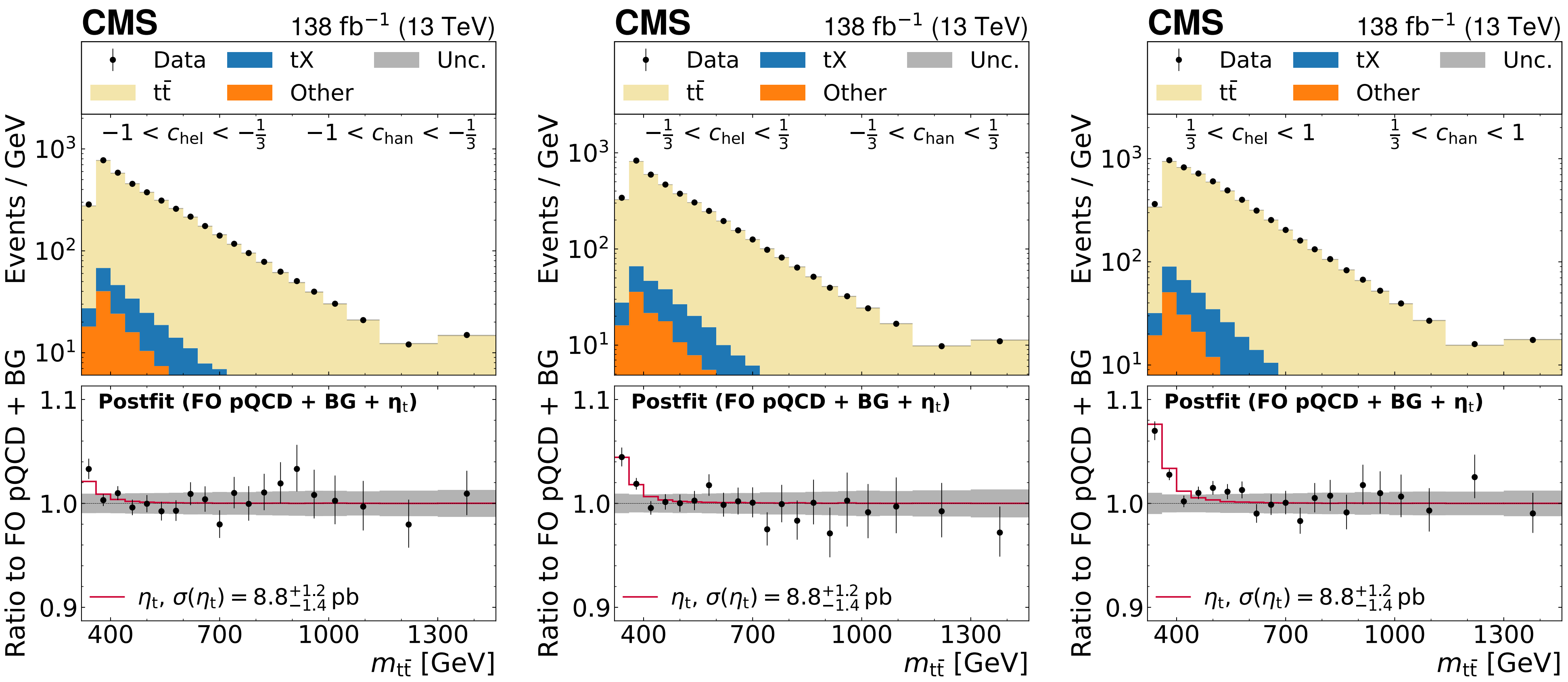


CMS Results

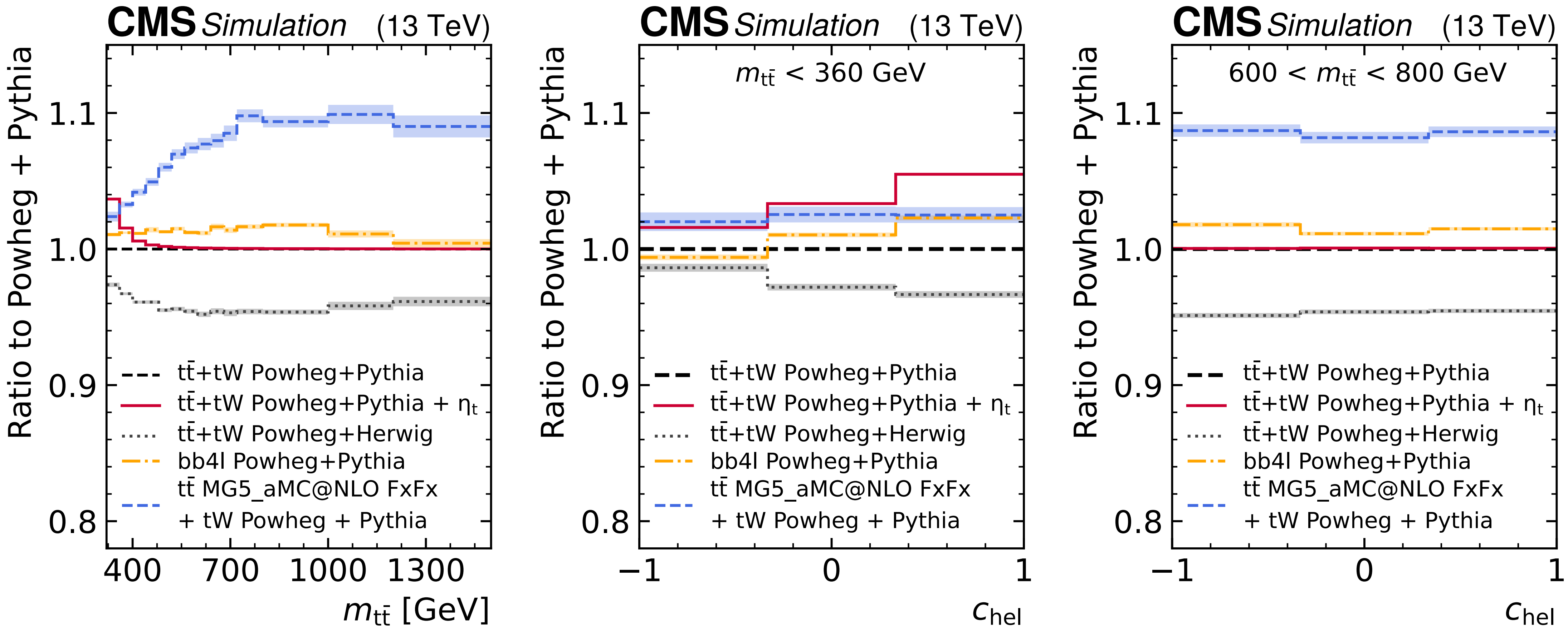
CMS Results

- arXiv:2503.22382, Rep. Prog. Phys. 88 (2025) 087801
- Use very similar analysis method compared with ATLAS
- Use toy model for signal

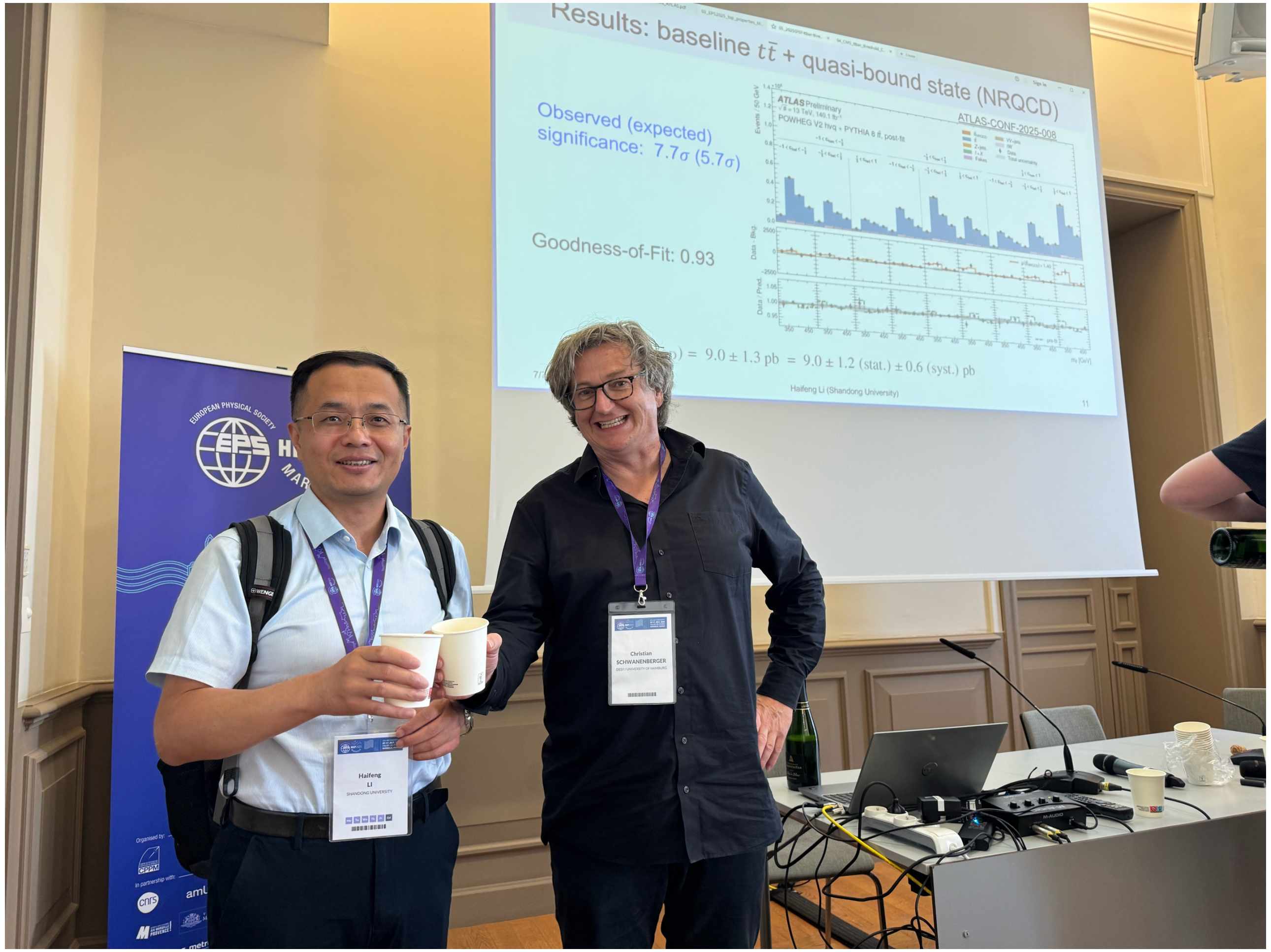
显著度大于5σ



Comparison of different models



- First report about ATLAS results in EPS-HEP2025 in Marseille, France
- Celebration after toponium talks from ATLAS and CMS
- All the ATLAS&CMS management who attended EPS-HEP2025 listened the two talks
- Was one of the highlights for EPS-HEP2025

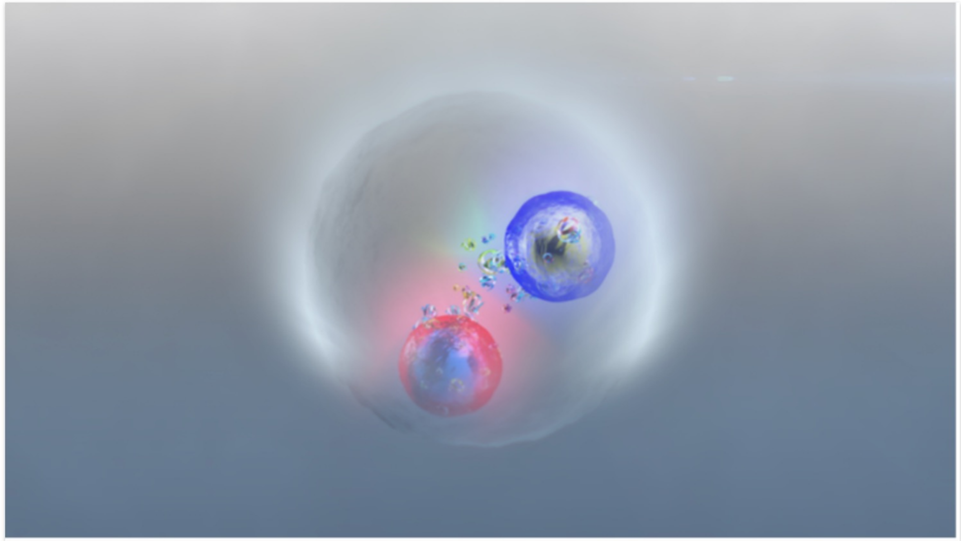


CERN Press Release after the ATLAS talk in EPS-HEP2025

Elusive romance of top-quark pairs observed at the LHC

The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union

8 JULY, 2025



Artist's impression of the short-lived union of a top quark and a top antiquark formed by the exchange of gluons. (Image: D. Dominguez/CERN)

An unforeseen feature in proton-proton collisions previously observed by the CMS experiment at CERN's Large Hadron Collider (LHC) has now been confirmed by its sister experiment ATLAS. The result, reported yesterday at the European Physical Society's High-Energy Physics conference in Marseille, suggests that top quarks – the heaviest and shortest-lived of all the elementary particles – can momentarily pair up with their antimatter counterparts to produce a "quasi-bound-state" called toponium. Further input based on complex theoretical calculations of the strong nuclear force -- called quantum chromodynamics (QCD) -- will enable physicists to understand the true nature of this elusive dance.

An unforeseen feature in proton-proton collisions previously observed by the CMS experiment at CERN's Large Hadron Collider (LHC) has now been confirmed by its sister experiment ATLAS. The result, reported yesterday at the European Physical Society's High-Energy Physics conference in Marseille, suggests that top quarks – the heaviest and shortest-lived of all the elementary particles – can momentarily pair up with their antimatter counterparts to produce a "quasi-bound-state" called toponium.

Andreas Hoecker - EPS-HEP2025 Summary

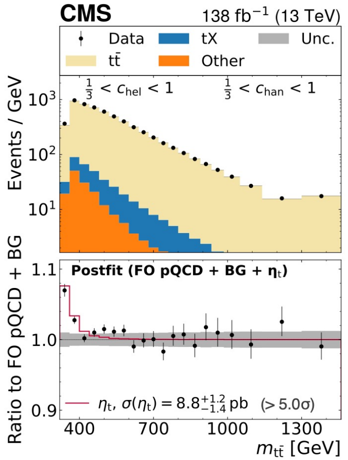
Top–antitop production at threshold

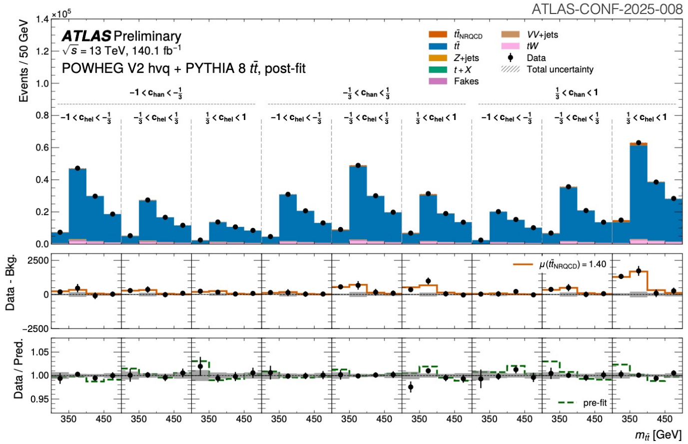
Josh Bendavid, Fabio Cerutti, Haifeng Li,
Roberto Salerno, Christian Schwanenberger

CMS observed enhancement near $t\bar{t}$ production threshold — observation confirmed by ATLAS at this conference

Strong interaction predicts highly compact, colour-singlet quasi-bound pseudoscalar $t\bar{t}$ states (negligible self-annihilation, top decays before)

The 'toponium' effect can be computed in non-relativistic QCD (NRQCD)

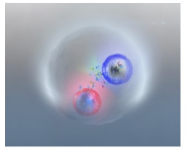




ATLAS used NRQCD model for threshold contribution (also alternative models studied)

Observed significance of 7.7σ for a cross section of 9.0 ±1.3 pb

(With CMS signal model ATLAS finds: 13.4 ±1.9 pb)



Elusive attraction among top-quark pairs

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CERN Courier

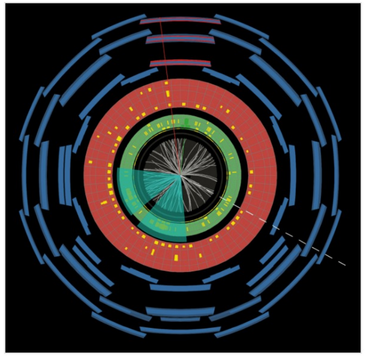
CERNCOURIER | Reporting on international high-energy physics

Physics ▾ Technology ▾ Community ▾ Magazine

STRONG INTERACTIONS | NEWS

ATLAS confirms top–antitop excess

9 September 2025



Quasi-bound candidate An event display of an interaction consistent with the formation of toponium in the ATLAS detector. The final state

At the LHC, almost all top–antitop pairs are produced in a smooth invariant-mass spectrum described by perturbative QCD. In March, the CMS collaboration announced the discovery of an additional 1% localised near the energy threshold to produce a top quark and its antiquark (*CERN Courier* May/June 2025 p7). The ATLAS collaboration has now confirmed this observation.

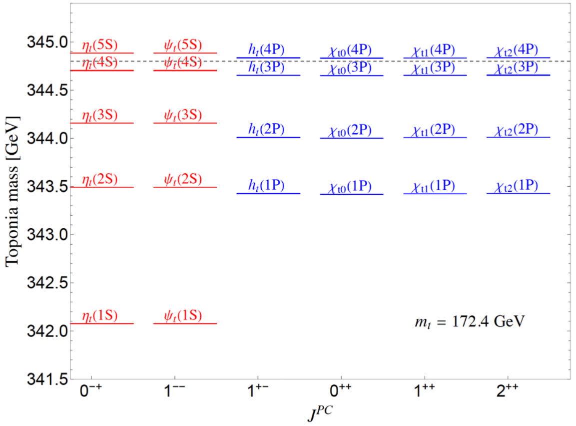
"The measurement was challenging due to the small cross section and the limited

Conclusions

- An excess of events is observed over the NNLO perturbative QCD prediction, with **7.7σ observed (5.7σ expected)** near the $t\bar{t}$ production threshold by ATLAS with LHC Run 2 data. [ATLAS-CONF-2025-008], [ATLAS Physics Briefing]
- This excess is consistent with **color-singlet, S-wave, quasi-bound $t\bar{t}$ states** predicted by NRQCD with cross-section of 9.0 ± 1.3 pb
- A more complete model from NRQCD calculation is used by ATLAS. Important advantage compared with recent CMS results (Rep. Prog. Phys. 88 (2025) 087801)
- **Observation of toponium** opens a new field to study NRQCD with top quarks

Offers novel insights into QCD

Possible to do "hadron spectroscopy" with top quarks



arXiv:2506.14552

FU, LI, YANG, LI, ZHANG, and SHEN, PRD 111, 114020 (2025)

Backup

Top quark pair reconstruction

- $t\bar{t}$ system reconstructed from the 2 leading b-jets, charged leptons, and $\vec{p}_T^{miss}$ using:
    1. Invariant mass of $\ell^+\nu_\ell b$ and $\ell^-\bar{\nu}_\ell\bar{b} = m_t = 172.5$ GeV
    2. Invariant mass of $\ell^+\nu_\ell$ and $\ell^-\bar{\nu}_\ell = m_W = 80.4$ GeV
    3. $\vec{p}_T^{miss}$ only from the two neutrinos: ν_ℓ and $\bar{\nu}_\ell$
- Ellipse method used to geometrically solve constraint equations for neutrino momenta
- m_t and m_W smeared if no solution found
- Solution found for 95% of events in SR – remaining discarded
- Resolution $\frac{|m_{t\bar{t}}^{reco} - m_{t\bar{t}}^{true}|}{m_{t\bar{t}}^{reco}} \sim 22\%$ at threshold
- Alternative methods tested did not improve sensitivity

NIM A 736 (2014) 169-178